

**FUELING AMERICAN INNOVATION AND
RECOVERY: THE FEDERAL ROLE IN
RESEARCH AND DEVELOPMENT**

HEARING
BEFORE THE
COMMITTEE ON THE BUDGET
HOUSE OF REPRESENTATIVES
ONE HUNDRED SIXTEENTH CONGRESS
SECOND SESSION

HEARING HELD IN WASHINGTON, D.C., JULY 8, 2020

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**FUELING AMERICAN INNOVATION
AND RECOVERY: THE
FEDERAL ROLE IN RESEARCH
AND DEVELOPMENT**

WEDNESDAY, JULY 8, 2020

HOUSE OF REPRESENTATIVES,
COMMITTEE ON THE BUDGET,
Washington, D.C.

The Committee met, pursuant to notice, at 1:07 p.m., via Webex, Hon. John A. Yarmuth [Chairman of the Committee] presiding.

Present: Representatives Yarmuth, Moulton, Boyle, Price, Schakowsky, Kildee, Panetta, Morelle, Scott, Jackson Lee, Peters; Womack, Woodall, Johnson, Flores, Holding, Crenshaw, and Burchett.

Chairman YARMUTH. The hearing will come to order.

Good afternoon, and welcome to the Budget Committee's hearing on Fueling American Innovation and Recovery: The Federal Role in Research and Development.

I want to welcome our witnesses who are here with us today.

At the outset, I ask unanimous consent that the Chair be authorized to declare a recess at any time to address technical difficulties that may arise with such remote proceedings.

Without objection, so ordered.

As a reminder, we are holding this hearing virtually in compliance with the regulations for committee proceedings pursuant to House Resolution 965.

First, consistent with the regulations, the Chair or staff designated by the Chair may mute participants' microphones when they are not under recognition for the purposes of eliminating inadvertent background noise.

Members are responsible for unmuting themselves when they seek recognition or when they are recognized for their five minutes. We are not permitted to unmute Members unless they explicitly request assistance. If I notice that you have not unmuted yourself, I will ask you if you would like staff to unmute you. If you indicate approval by nodding, staff will unmute your microphone. They will not unmute you under any other conditions.

Second, Members must have their cameras on throughout this proceeding and must be visible on screen in order to be recognized. As a reminder, Members may not participate in more than one committee proceeding simultaneously.

Finally, to maintain safety, in light of the Attending Physician's new guidance, any Members present in the hearing room must

wear a mask at all times when they are not speaking. For those Members not wanting to wear a mask, the House rules provide a way to participate remotely from your office without being physically present in the hearing room.

Now I am proud to introduce our witnesses this afternoon. We will be hearing from Dr. Sudip Parikh, CEO at the American Association for the Advancement of Science; Dr. Paul Romer, a professor in economics at New York University; the Honorable Deborah Wince-Smith, president and CEO at the Council on Competitiveness; and Dr. Willy Shih, professor of management practice at Harvard Business School.

I will now yield myself five minutes for an opening statement.

Since our last hearing, there have been more than 600,000 new confirmed coronavirus cases and more than 9,000 Americans have succumbed to the virus. Our economy is in free-fall, and unemployment is forecast to remain in the double digits for the foreseeable future. Across the country, men, women, and children are still marching and advocating for a more just and peaceful future.

While the state of our Union remains uncertain, there is hope and there are answers yet to be discovered. Reinvigorating our science and engineering capabilities could help our nation address the crises we face today while better preparing our nation for the future.

But despite its immense potential and history of success, the federal commitment to research and development has declined, while this Administration systematically suppresses, distorts, ignores, or thwarts scientific research in the name of false hope.

Last year, nondefense discretionary funding as a percent of GDP equaled its lowest level in 50 years, and government support for science and engineering has been one of the casualties. Federal R&D funding as a share of the economy has fallen from barely 1.9 percent in the mid-1960's to less than 0.7 percent in 2018, hindering advancements and slowing innovation. Not surprisingly, we are increasingly outranked by global competitors like China on international benchmarks of competitiveness.

Now, COVID-related disruptions and the Administration's failure to take this health threat seriously threaten to further derail U.S. innovation. Meanwhile, other nations are working to solve both the global health and economic crises by ramping up investments in R&D, spurring their recovery while planning for future advancements that will help them maintain their competitive edge in the global market.

Experts have stressed the importance of aggressive, responsible, and strategic investments to our recovery from COVID-19 and the economic fallout. Aside from the obvious, like developing vaccines and treatments for COVID-19, Federal R&D investments would also help spur an inclusive recovery, boost regional economies, and put Americans back to work.

Targeting federal investments to increase diversity, equity, and inclusion in the research and innovation ecosystem would allow us to fully tap into talents of all our citizens and would accelerate discovery, while also increasing GDP per capita by as much as 3 to 4 percent.

Localized clusters of federally supported R&D in labs and universities can increase regional economic opportunities, creating jobs in the short and long term. We have seen this work before. Evidence indicates that Recovery Act stimulus investments in R&D had a large and positive employment effect.

This investment would attract, not displace, additional private investment while creating new opportunities across the country and fueling revolutionary solutions to pressing problems. It could spur entirely new industries that many established companies find too risky or cost-prohibitive to explore.

Recognizing the value of federal investments, Congress has begun the work to restore R&D funding. The Bipartisan Budget Agreement of 2019 added significantly to both defense and non-defense discretionary funds that would otherwise have been at austerity levels. And Congress has appropriated additional supplemental resources for NIH and CDC as we fight the coronavirus pandemic.

But Congress needs a committed partner in the White House to ensure scientific evidence, data, and research are once again incorporated meaningfully into federal policy. Instead, the Trump Administration has routinely sabotaged the work of federal scientists and experts, prioritized politics over progress, buried data, purposely misled the public on issues ranging from climate change to the impact of chemical exposure on our children's health. And now this disdain for science has made America a global hotspot for coronavirus infection.

It shouldn't take a lawsuit for this Administration to release data on the racial disparities of coronavirus infections. Scientists and experts should never be muzzled and prevented from sharing potentially lifesaving information with the public. The American people are being forced to withstand the tragic results of the Administration's devotion to ignorance in favor of political points and division.

From putting a man on the Moon and the invention of the internet to groundbreaking medical advancements, federal investments in R&D have fueled our economic growth, helped us tackle problems home and abroad, and made America a beacon of innovation and discovery. Without a renewed commitment to science and innovation, we risk squandering our recovery and the opportunity to move our nation forward as a global force for good.

We will not be able to defeat the virus and foster an inclusive recovery if our communities don't have the tools, knowledge, and freedom to do it. That will take investment and an administration that respects science and facts.

I look forward to this important discussion, and I am eager to hear from our witnesses.

I now yield to the Ranking Member, Mr. Womack, to unmute his microphone and give his opening statement.

[The prepared statement of Chairman Yarmuth follows:]

Chairman John A. Yarmuth
Hearing on Fueling American Innovation and Recovery:
The Federal Role in Research and Development
Opening Statement
July 8, 2020

Since our last hearing, there have been more than 600,000 new confirmed coronavirus cases and more than 9,000 Americans have succumbed to the virus. Our economy is in free fall and unemployment is forecast to remain in the double-digits for the foreseeable future. Across the country, men, women, and children are still marching and advocating for a more just and peaceful future. While the state of our nation remains uncertain, there is hope and answers yet to be discovered.

Reinvigorating our science and engineering capabilities can help our nation address the crises we face today, while better preparing our nation for the future. But despite its immense potential and history of success, the federal commitment to R&D has declined, while this Administration systematically suppresses, distorts, ignores, or thwarts scientific research in the name of false hope. Last year, non-defense discretionary funding as a percent of GDP equaled its lowest level in 50 years – and government support for science and engineering has been one of the casualties. Federal R&D funding as a share of the economy has fallen from barely 1.9 percent in the mid-1960s to less than 0.7 percent in 2018, hindering advancements and slowing innovation. Not surprisingly, we are increasingly outranked by global competitors like China on international benchmarks of competitiveness. Now COVID-related disruptions and the Administration's failure to take this public health threat seriously threaten to further derail U.S. innovation. Meanwhile, other nations are working to solve both the global health and economic crises by ramping up investments in R&D – spurring their recovery while planning for future advancements that will help them maintain their competitive edge in the global market.

Experts have stressed the importance of aggressive, responsible, and strategic investments to our recovery from COVID-19 and the economic fallout. Aside from the obvious – like developing vaccines and treatments for COVID-19 – federal R&D investments would also help spur an inclusive recovery, boost regional economies, and put Americans back to work. Targeting federal investments to increase diversity, equity, and inclusion in the research and innovation ecosystem would allow us to fully tap into talents of all our citizens and would accelerate discovery while also increasing GDP per capita by as much as 3 to 4 percent.

Localized clusters of federally supported R&D in labs and universities can increase regional economic opportunities, creating jobs in the short- and long term. We have seen this work before: Evidence indicates that Recovery Act stimulus investments in R&D had a large and positive employment effect. This investment would attract - not displace - additional private investment while creating new opportunities across the country and fueling revolutionary solutions to pressing problems. It could spur entirely new industries that many established companies find too risky or cost-prohibitive to explore.

Recognizing the value of federal investments, Congress has begun the work to restore R&D funding. The Bipartisan Budget Agreement of 2019 added significantly to both defense and non-defense discretionary funds that would have been at austerity levels – and Congress has appropriated additional, supplemental resources for NIH and CDC as we fight the coronavirus pandemic. But Congress needs a committed partner in the White House to ensure scientific evidence, data, and research are once again incorporated meaningfully into federal policymaking.

Instead, the Trump Administration has routinely sabotaged the work of federal scientists and experts, prioritized politics over progress, buried data, and purposefully misled the public on issues ranging from climate change to the impact of chemical exposure on our children's health.

And now this disdain for science has made America a global hotspot for coronavirus infection. It shouldn't take a lawsuit for this Administration to release data on the racial disparities of coronavirus infections.

Scientists and experts should never be muzzled and prevented from sharing potentially life-saving information with the public. The American people are being forced to withstand the tragic results of this Administration's devotion to ignorance in favor of political points and division.

From putting a man on the moon and the invention of the internet to groundbreaking medical advancements, federal investments in R&D have fueled our economic growth, helped us tackle challenges at home and abroad, and made America a beacon of innovation and discovery. Without a renewed commitment to science and innovation, we risk squandering our recovery and the opportunity to move our nation forward as a global force for good. We will not be able to defeat this virus and foster an inclusive recovery if our communities don't have the tools, knowledge, and freedom to do it. That will take investment – and an Administration that respects science and facts.

I look forward to this important discussion and I am eager to hear more from our witnesses.

Mr. WOMACK. Thank you, Mr. Chairman, for holding this hearing.

And thank you to the witnesses who are joining us today.

Our nation's strong innovation ecosystem has always been driven by the pioneering spirit on which America was founded. Throughout the centuries, we have leveraged research and development to make unthinkable progress across industries and drive the United States—indeed, the world—forward. This has enabled our economic competitiveness in many of the country's public missions: national security, healthcare, infectious disease response, rural development, disaster preparedness and response, and a whole lot more.

Thanks to R&D, advancements that could only once be imagined are now possible. Whether it is developing the vaccine for COVID-19, next-generation computers and phones, carbon capture and storage, or the next stealth multirole combat aircraft fighter, the delivery of these capabilities has been rooted in the ability to unleash innovation, research, and technology.

I saw an example of this firsthand this week as I visited a company in my own district, NOWDiagnostics in Springdale, Arkansas. They develop simple diagnostic tests which require nothing more than a drop of blood and a few minutes to yield results. Their products cover everything from a COVID-19 antibody test to screenings for Malaria and Ebola. Just one example of the many American companies producing cutting-edge technology and solutions.

So how do we continue to encourage these types of breakthroughs? Washington should support private industry, which has led a vast majority of investment, and promote policies that encourage companies to continue to unleash opportunity in this critical space. This supporting role of the federal government should focus on resources for R&D in areas such as early stage research and streamlining regulations.

As a Member of the Appropriations Committee, I've advocated for federal research funding for critical NIH programs, including Alzheimer's, ALS, diabetes, and pediatric cancer research. We also can't overlook national-security priorities, like the Biomedical Advanced Research and Development Authority, BARDA, which helps us combat bioterrorism and other emerging health threats.

It is for these programs that I will continue to voice my concern for the true challenge that threatens all critical federal programs, including R&D initiatives—that is, our out-of-control deficit and debt. We're spiraling toward a fiscal crisis, and once we get there, once it hits, there will be zero money to fund these critical programs.

I've said over and over again, as an appropriator, one of my chief concerns is that we continue to have major food fights in Appropriations on the House floor about how we fund the discretionary side of the budget. There won't be any money for R&D if we don't tackle the real problems facing our country, and that is on mandatory spending.

It has grown from 34 percent of the federal budget in 1965 to 70 percent today. It is projected to grow to 76 percent in 2030. Discretionary spending, which includes funding for health research, space exploration, and the National Science Foundation, has declined

from 66 percent of the federal budget in 1965 to just 30 percent today. It is literally being squeezed away.

What this Committee should be focusing on is putting together a budget that addresses out-of-control mandatory spending, the driver of our unsustainable deficits and debt. If policymakers want to prioritize R&D funding, they must first tackle this threat.

It's not easy. It's going to require political courage. Indeed, some Members will go home as a result. Congress must get back to making the tough choices. It won't be an easy job, but it has to be done. This is the only way critical federal programs, both discretionary and mandatory, will continue to exist for current and future generations.

I look forward to hearing from our witnesses today.

And I'll take just a quick moment of personal privilege to say that, on the subject of R&D, my good friend Joe Steinmetz, the chancellor at the University of Arkansas, has made research an important cornerstone of his administration at the U of A in Fayetteville, our land-grant university. I expect within the next several days there will be a major announcement of a funding source for a major research institute on our very own campus in Fayetteville, Arkansas, and I look forward to sharing that news with you at the appropriate time.

Mr. Chairman, as always, thank you for your leadership. I yield back the balance of my time.

[The prepared statement of Steve Womack follows:]

**RANKING MEMBER STEVE WOMACK'S (R-AR-3) OPENING REMARKS**

*Hearing: Fueling American Innovation and Recovery
The Federal Role in Research and Development*

July 8, 2020

(As Prepared for Delivery)

Thank you, Chairman Yarmuth, for holding this hearing, and thank you to our witnesses for joining us today.

Our nation's strong innovation ecosystem has always been driven by the pioneering spirit on which America was founded. Throughout centuries, we have leveraged research and development (R&D) to make unthinkable progress across industries and drive the United States forward.

This has enabled our economic competitiveness and many of the country's public missions: national security, health care delivery, infectious disease response, rural development, disaster preparedness and response, and more.

Thanks to R&D, advancements that could once only be imagined are now possible. Whether it's developing the vaccine for COVID-19, next generation computers and phones, carbon capture and storage, or the next stealth multi-role combat aircraft fighter – the delivery of these capabilities has been rooted in the ability to unleash innovation, research, and technology.

I saw an example of this firsthand earlier this week as I visited NOWDiagnostics in Springdale, Arkansas. They develop simple diagnostic tests, which require nothing more than a drop of blood and a few minutes to yield results. Their products cover everything from a COVID-19 antibody test to screenings for Malaria and Ebola. It's just one example of the many American companies producing cutting-edge solutions.

So how do we continue to encourage these types of breakthroughs? Washington should support private industry — which has led a vast majority of investment — and promote policies that encourage companies to continue to unleash opportunity in this critical space. This supporting role of the federal government should focus on resources for R&D in areas — such as early-stage research — and streamlining regulations.

As a member of the Appropriations Committee, I have advocated for federal research funding for critical NIH programs, including Alzheimer's, ALS, diabetes, and pediatric cancer research. We also can't overlook national security priorities like the Biomedical Advanced Research and Development Authority, which helps us combat bioterrorism and other emerging health threats.

It's for these programs that I will continue to voice my concern of the true challenge that threatens all critical federal programs, including R&D initiatives. That is our out-of-control deficit and debt. We are spiraling toward a fiscal crisis and, once it hits, there will be zero money to fund critical programs. There will be no funding for R&D.

Mandatory spending has grown from 34 percent of the federal budget in 1965 to 70 percent today and is projected to grow to 76 percent in 2030. Discretionary spending, which includes funding for health research, space exploration, and the National Science Foundation, has declined from 66 percent of the federal budget in 1965 to 30 percent today, to a projected 24 percent in 2030.

What this committee should be focusing on is putting together a budget that addresses out-of-control mandatory spending, the driver of our unsustainable deficits and debt. If policymakers want to prioritize R&D funding, they must first tackle this threat.

Congress must get back to making the tough choices we have been tasked to do. It won't be an easy job, but it needs to be done. This is the only way critical federal programs — both discretionary and mandatory — will continue to exist for current and future generations.

With that, I look forward to hearing from our witnesses today, and I look forward to today's discussion. Thank you, Mr. Chairman. I yield back.

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Chairman YARMUTH. Thank you, Mr. Womack, for your opening statement.

In the interest of time, if any other Members have opening statements, they may submit those statements electronically to the clerk for the record.

Chairman YARMUTH. Once again, I want to thank our witnesses for being here this morning.

The Committee has received your written testimony, and they will be made part of the formal hearing record. Each of you will have five minutes to present your oral remarks. As a reminder, please unmute your microphone before speaking.

Dr. Parikh, please unmute your microphone and begin when you are ready.

STATEMENTS OF SUDIP PARIKH, PH.D., CHIEF EXECUTIVE OFFICER, AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE; PAUL ROMER, PH.D., PROFESSOR OF ECONOMICS, NEW YORK UNIVERSITY; THE HON. DEBORAH WINCE-SMITH, PRESIDENT AND CHIEF EXECUTIVE OFFICER, COUNCIL ON COMPETITIVENESS; AND WILLY SHIH, PH.D., PROFESSOR OF MANAGEMENT PRACTICE, HARVARD BUSINESS SCHOOL

STATEMENT OF SUDIP PARIKH, PH.D.

Dr. PARIKH. Thank you. Good afternoon, Chairman Yarmuth, Ranking Member Womack, and Members of the Committee. Thank you so much for the opportunity to testify today.

I am Sudip Parikh, and I have the privilege of being the chief executive officer of the American Association for the Advancement of Science and also the publisher of the Science family of journals. Our mission is to advance science, engineering, and innovation for the benefit of all people, or, to put it more simply, to advance science and serve society.

Today, I want to briefly discuss three reasons why I think today's hearing is incredibly timely and then provide three recommendations to the Committee—to the Budget Committee.

First, science and engineering are more important now than ever in our national preparation and response to current crises, including COVID-19 but also ongoing challenges such as climate change and economic competitiveness.

In response to these crises, the federal government has a vital leadership and coordination role that can be the difference between success and failure. Successfully preparing for and responding to COVID-19, climate change, and threats to competitiveness will require the federal government to play the role of a quarterback.

Second, science has a substantive role to play in advancing shared opportunity and fair treatment for everyone by addressing challenges in the scientific enterprise and providing an evidence base for national policymaking. Science and evidence must be integrated into the policymaking progress to advance shared opportunity and fair treatment for all.

Science, especially social science, is key to unlocking our path forward. The work of scientists is critical to better understanding and interpreting data on government spending on incarceration, of-

ficer-involved shootings, crime reduction, health disparities, and other relevant topics.

To be able to address national policymaking issues, science must also look inward to ensure that the scientific enterprise is addressing our own biases. The core of our nation's innovation ecosystem is more than just funding for research; it is also the investment we make in people.

Third, it is time to increase our investments and update our federal policy and investment framework to continue harnessing the scientific research that builds the U.S. economy and increases the safety and well-being of all Americans.

Right now, our nation is celebrating the 75th anniversary of "Science: The Endless Frontier," written by Vannevar Bush in 1945. That provided a policy framework that envisioned a national partnership between government, academia, and industry to harness basic scientific knowledge for security and well-being.

That framework has served as the basis for our investment in advancing basic research and industrial innovation and economic success, but, frankly, it is time for an update. The scientific enterprise has evolved far beyond Bush's original vision and now delivers scientific advances, medical cures, innovative technology products, raised standards of living, economic growth, and, frankly, awe-inspiring understanding of the universe.

That scientific ecosystem is nourished by broad and varied federal investment in research and development: universities and non-profits; institute-based scientists driving thought leadership; innovative financial instruments to bring private-sector risk capital; entrepreneurs who are driven to move scientific advances from the lab to the consumer; industry investment, particularly in development; and agile regulatory agencies able to keep up with the progress of science and technology and factor it into their decision-making. Each piece of that ecosystem is important, but it all begins with the federal role.

Our global competitors have seen our success and are paying it the highest compliment; they are copying it. The "2020 State of U.S. Science and Engineering" report shows that, although the U.S. spent more on R&D than any other country in 2017, other nations are catching up. And, since 2000, the American share of global R&D has declined from 37 to 25 percent, as U.S. research intensity, or R&D as a share of GDP, is well below its peak level and below the investment levels of nine other countries.

How much should we invest? Well, as Chairman Yarmuth pointed out, federal funding for research and development peaked at 1.9 percent of GDP. We should be investing more than we are right now in order to compete with other nations in science, technology, and innovation. There are many ways to look at this, and I provide additional details in my written testimony.

And this takes us to my recommendations.

The U.S. should update the Bush framework for advancing science and serving society, with an emphasis on full-spectrum innovation, including fundamental science, mission-driven technology, and useful knowledge programs that meet local, national, and international needs, with the federal government as a key partner.

The United States should increase total investment in R&D as a percentage of GDP to 1.9 percent, which would require increases of approximately 11 percent per year. This would match the peak we achieved more than five decades ago and put us firmly back into the top three countries for research intensity globally by 2035.

And, last, scientific leaders must ensure that the scientific enterprise is supporting opportunities for all by addressing challenges within the scientific enterprise and providing the evidence base to inform national policymaking. This is just critical to ensuring a fairer scientific enterprise and a fairer world.

Thank you for having me today, and I look forward to our discussion.

[The prepared statement of Sudip Parikh follows:]

Written Testimony of Dr. Sudip Parikh
American Association for the Advancement of Science
Before the House Budget Committee
U.S. House of Representatives
July 8, 2020

Chairman Yarmuth, Ranking Member Womack and Members of the Committee, thank you very much for the opportunity to testify before the Committee. I am Sudip Parikh, chief executive officer at the American Association for the Advancement of Science. AAAS is the largest general scientific society in the United States and the world, and the publisher of the *Science* family of journals. Our mission is to advance science, engineering, and innovation throughout the world for the benefit of all people or – put more simply – to advance science and serve society.

The topic of today's hearing, "Fueling American Innovation and Recovery: The Federal Role in Research and Development," is incredibly timely for at least three reasons.

First, science and engineering are more important now than ever in our national preparation and response to current crises, including COVID-19, and ongoing challenges such as climate change and economic competitiveness.

Second, science has a substantive role to play in advancing shared opportunity and fair treatment for all Americans by addressing challenges in the scientific enterprise and providing an evidence base for national policy making.

Third, it is time to increase our investments and update our federal policy and investment framework to continue harnessing scientific research and seize the opportunities in front of us to build the U.S. economy and increase the safety and well-being of all Americans.

Today, I will briefly discuss each of these and provide recommendations to the Committee.

In summary, these recommendations are:

- 1) The United States should update the Vannevar Bush framework for advancing science and serving society, including prescriptions for how the federal government should coordinate science in response to crises.
- 2) The United States should increase federal investment in R&D as a percentage of GDP to 1.9%, requiring increases of approximately 11% per year.
- 3) Scientific leaders should ensure that the scientific enterprise is supporting opportunities for all by addressing challenges within the scientific enterprise and by providing the evidence base to inform national policymaking.

Science and engineering are more important now than ever in our national preparation and response to current crises, including COVID-19, and ongoing challenges such as climate change economic competitiveness.

Preparing and responding to crises and ongoing challenges require leadership and coordination for the efficient allocation of resources. Many investments are being made by government, industry, and philanthropy. But even huge investment is not a guarantee of success. In response to crises, the federal government has a vital leadership and coordination role that can be the difference between success and failure. Successfully preparing for and responding to COVID-19, climate change, and threats to competitiveness will require the federal government to play the role of quarterback.

Science and engineering will be critical to ending the COVID-19 crisis. Evidence-based public health measures, like wearing masks, physical distancing, and contact tracing are needed to slow the progression of the disease until our investments in life sciences and advanced manufacturing deliver vaccines and treatments at a national scale. The basic research and characterization of the novel coronavirus that causes the COVID-19 disease has been extraordinary. In the span of six months, scientists have gone from the first isolation of the virus to a complete molecular characterization of the virus. We have all the basic information required to develop a first round of treatments and vaccines. We haven't gotten the public response right, but the scientific characterization and drive toward treatments and vaccine in very short order is unprecedented. None of this would have been possible without the federal role in research and development.

But COVID-19 is not the only disease affecting Americans during this time. We must ensure that the incredible progress made to lower the death rates for cancer and heart disease continue. For the first time in history, we may be able to cure diseases that have plagued humanity for millennia. Clinical trials are ongoing for what could be cures for sickle cell anemia and beta thalassemia. Patients with night blindness have been cured already. Many more treatments and cures are on the horizon, and none of this is possible without the federal role in research and development and its interplay with the rest of the scientific ecosystem.

To continue to improve our understanding of the climate challenge, we must continue to invest in Earth science missions, as the White House has highlighted through its National Plan for Civil Earth Observations.¹ Reducing carbon emissions and addressing climate change will require science and policy changes. A recent analysis by the International Energy Agency also highlights the importance of technology investments for climate mitigation and response: many of the technologies needed to hit net-zero emissions are still in the early stages, requiring further innovation to achieve cost reductions and performance improvements.² The federal government has a clear role to play.

R&D investments are also critical to securing our nation's future in manufacturing. As this Committee well knows, manufacturing employment has declined precipitously for decades. This is not only a challenge to the American middle class, but to our national security since we rely on foreign sources for critical technologies like semiconductors. We also know that R&D investments are critical sources for manufacturing innovation: manufacturers get some of their most important and profitable inventions from sources outside the firm, including universities and startups.³ Accelerating investments in robotics,

advanced materials, intelligent systems, and related fields can help to restore manufacturing competitiveness.

These are just a few examples of the many areas in which federal leadership, coordination, and investment in science and engineering will be critical to our national preparation and response to current and future crises.

Science has a substantive role to play in advancing shared opportunity and fair treatment for all Americans by addressing challenges in the scientific enterprise and providing an evidence base for national policy making.

Scientists have an essential role to play in addressing the systemic inequities we have seen come to the forefront of the public consciousness over the past several weeks. Science, at its core, is the process of removing bias and following evidence wherever it leads. The work of scientists is critical to better understanding and interpreting data on government spending on incarceration, officer-involved shootings, crime reduction, efficacy of police equipment, community policing, and other relevant topics. Science and evidence must be integrated into the policymaking process to advance shared opportunity and fair treatment for all Americans. It is vital to further our understanding of the mechanisms that drive our world and our economy today. To know where we want to go, we must understand where we are, and science—especially social science—is key to unlocking our path forward.

To be able to address national policymaking issues, science must also look inward to ensure that the scientific enterprise is addressing its own biases.

Many scholars have explored the relationship of diversity and excellence, innovation and productivity. We know that our nation's research and education has far to go to reflect a diverse and inclusive system, and to improve exposure to invention and innovation for people of all backgrounds. Why is this important to innovation and our economy? Science has shown that the diversity of people and cultures that one brings to scientific research and discovery can improve the inputs and the outcomes. Further, enabling broader participation in innovation would allow the United States to achieve a net increase in innovative activities—and that's good for everyone.

Take the following observation of serial inventor and innovator Joseph DeSimone: "There is no more fertile ground for innovation than a diversity of experience. And that diversity of experience arises from a difference of cultures, ethnicities, and life backgrounds. A successful scientific endeavor is one that attracts a diversity of experience, and cultivates those differences, acknowledging the creativity they spark."⁴

The core of our nation's innovation ecosystem is more than just funding for research. As my AAAS colleague Dr. Shirley Malcom stated in Congressional testimony last year, it is also the investment we make in people: "not just the scientists, engineers and mathematicians in our colleges, universities, industries, national labs and biomedical facilities, but also the STEM teachers, technicians, managers, financiers, patent attorneys, and more, whose collective efforts, grounded in science, fuel the innovation economy. STEM knowledge and skills are not just requirements for scientists and engineers but for people throughout the workforce and across the spectrum of our society—from farmers utilizing

weather data and robotics to cultivate and manage crops, to those who care for us when we are sick using unimaginable diagnostic tools.”

At AAAS, we are a gatekeeper organization. Publishing in our journals, serving in our leadership, and winning our fellowships and awards are waypoints to scientific influence and success. We are working to ensure our processes and gatekeeping functions are diverse and inclusive. We are starting with transparency on representation within each of these functions and awards, and providing plans for increasing representation. We must continue to support opportunities for STEM students and professionals across the spectrum of our society. AAAS is working to do this through initiatives such as SEA Change,⁵ the Emerging Researchers National Conference,⁶ Entry Point!,⁷ the L’Oréal USA For Women in Science Fellowship Program,⁸ and more – but there is still much work to be done. This work must and will continue and grow – along with work at other scientific societies, government agencies, and in industry.

It is time to update our policy and federal investment framework to continue harnessing scientific research for increased well-being.

Based on the issues, challenges, and opportunities stated above, it is clear that our framework for scientific investment is ready for a refresh. Our nation is celebrating the 75th anniversary of *Science: The Endless Frontier*, written by Vannevar Bush in 1945. *The Endless Frontier* provided a policy framework that envisioned a new national partnership between government, academia and industry to harness basic scientific knowledge for security and well-being. It advocated an approach that has become known as the “linear model,” whereby the federal government invests in basic research at universities and laboratories, which in turn catalyzes industrial innovation. Bush’s policy framework has served as the basis for our investment and success in advancing basic research into industrial innovation and economic success for the past 75 years – **but it’s time for an update.**

Today’s science and innovation ecosystem is far more complex, and the federal role in that system and in society far more varied, than the simple story Bush envisioned. Indeed, some of the greatest instances of value and impact delivered by the federal R&D system only bear minimal resemblance to that vision.

What, exactly, are the ways in which federal R&D investments contribute value to the nation?

New discoveries from fundamental science. Federally funded basic research – which seeks fundamental understanding of natural phenomena – has been a staple of the U.S. research enterprise for much of the past century. While Bush’s analysis is overly simplistic for today’s world, it remains true that basic science is vital. While in recent years, industry investment in basic science has risen in certain sectors like pharmaceuticals, electronic instruments, and aerospace,⁹ the federal government nevertheless remains the largest funder of basic science in the United States – and the only funder able to sustain long-term investments with highly uncertain and unpredictable outcomes across the full array of scientific disciplines.

As a result, federally funded basic research is a critical source of unexpected but world-changing discoveries. Several years ago, AAAS and partners worked to establish the Golden Goose Award to recognize some of these unexpected achievements, for example:

- The National Science Foundation funded the discovery of a certain kind of bacteria living in the hot springs in Yellowstone National Park. The particular enzymes discovered in this bacterium led to the development of polymerase chain reaction (PCR), a method for replicating billions of DNA copies from small fragments. PCR is a pivotal invention in the annals of science and a foundational tool for modern genetic testing – including COVID-19 testing today.¹⁰
- Endotoxins are a toxic substance found on the outer walls of bacteria, and are dangerous to humans. Today the *Limulus* amebocyte lysate (LAL) test is the global standard for screening for endotoxin contamination, with millions of tests performed each year. The test is based on discoveries from research into the circulatory system of horseshoe crabs.¹¹ The work was funded by the Atomic Energy Commission, the National Institutes of Health, and the U.S. Public Health Service.
- Years of funding support from the National Science Foundation and the U.S. Navy for research into the fundamental properties and amplification of microwave radiation – which was derided at the time as a waste of resources – led directly to the invention of laser technology, as well as a Nobel Prize.¹²

Broadly, federal research is effective in producing discoveries that lead to high-impact, novel inventions, often in technology areas that have not yet received much industry attention.¹³ In considering the value of scientific research, it is worth recalling physicist Michael Faraday's reply in the 1850s to William Gladstone, then British chancellor of the exchequer. Questioned about the practical value of electricity research, Faraday answered: "One day, sir, you may tax it."

New technologies and useful knowledge. The federal government also funds valuable research for nearer-term uses and to address public challenges. It catalyzes the development of next-generation technology in high-risk or underinvested areas. Applied science programs can have major, immediate, and long-lasting impacts on the day-to-day lives of ordinary Americans, and are integral for achieving public missions in health, national security, environmental stewardship, and other areas – especially when they are able to effectively engage users of the knowledge they produce. For example:

- Public agricultural research funded by the U.S. Department of Agriculture (USDA) has produced enormous value for Americans in enhancing agricultural productivity, nutrition, and safety, with very high rates of return on such investments according to recent economic studies.¹⁴ Agricultural innovation has a decidedly regional character,¹⁵ and the benefits of public agricultural research are also regional: public research spending in a given state has a clear effect on technical change, and in turn productivity, in that state and its immediate neighbors.¹⁶ This local orientation toward applied knowledge helped motivate the 1887 establishment of USDA experiment stations via the Hatch Act, which had been in place for over half a century by the time Bush wrote *The Endless Frontier*.
- Particularly relevant to our time, USDA scientists pursue research to understand what are known as zoonotic diseases, those diseases that originate in animals and can jump to humans. For instance, in 2008, the Animal and Plant Health Inspection Service partnered with Agricultural Research Service scientists and the Centers for Disease Control and Prevention (CDC) to implement a swine flu surveillance pilot project. This in turn provided crucial groundwork for surveillance during the subsequent H1N1 outbreak in 2009. As we continue to grapple with COVID-19, USDA's years of leadership in zoonotic disease science is a valuable resource now and when the next health threat emerges.¹⁷

- The National Oceanic and Atmospheric Administration (NOAA) has in recent years leveraged the agency's supercomputing resources with data from thousands of U.S. Geological Survey streamgages to deploy the new National Water Model (NWM), a tool that vastly improves flood forecasting across the continental United States. It provides timely, reliable, high-resolution forecasts every hour for millions of river locations that would otherwise not have them, providing utility for emergency responders, local water infrastructure managers, and other local officials.

Some of the most powerful innovations emerging from federal R&D come not from pure serendipity, but from what has been called "connected science" or "channeled curiosity": the purposeful coupling of risky research with real-world challenges and outcomes.¹⁸

For example, NSF's Engineering Research Centers (ERC) program is emblematic of this approach, combining fundamental science, technology prototyping, industry partnerships, and sustained long-term support. This approach has yielded hundreds of discoveries, inventions, patents, and patent licenses along with dozens of spinoff firms, returning many millions of dollars to the economy.¹⁹ Successes include, for instance, the first FDA-approved artificial retina in the United States, which in addition to the ERC program's support received funding from NIH and the Department of Energy.²⁰

The classic model for this approach is embodied in the Defense Advanced Research Projects Agency (DARPA), which has helped drive world-changing innovations in microelectronics, wireless communications, GPS, synthetic biology, stealth, and other areas. The innovative DARPA model, so valuable for defense technology, has begun to proliferate into other areas of the federal enterprise, with intriguing results.

One advantage of this model is its potential for dual impact on discovery *and* invention, as seen with the achievements of the Advanced Research Projects Agency-Energy (ARPA-E). ARPA-E has been highly effective in advancing fields of science (through new journal articles) and *simultaneously* advancing breakthrough technologies (through new patented inventions),²¹ while funding projects that are too risky even for venture capital.²²

Skills, networks, and collaborations. While the popular image of the lone, heroic scientist laboring away in her lab may persist, the reality is modern science and innovation increasingly relies on teamwork. Thus, a major way federal research delivers value is through training talented researchers and engineers supported by the spectrum of federal STEM education programs, and through the creation of knowledge networks.

For instance, DARPA helped to seed the modern field of materials science and engineering by establishing Interdisciplinary Labs in 1960 at Cornell, Northwestern, and the University of Pennsylvania, with several more the following year. The goal of these labs was to pull together the varying disciplinary strands relevant to materials science – including physics, metallurgy, and chemistry – which until then had generally been fragmented in separate university departments, and to produce a generation of skilled materials scientists and engineers able to think in these terms. The lab program was instrumental in creating a new interdisciplinary "materials science" community, and a quarter century later American universities boasted roughly 100 materials science departments.²³

The idea of knowledge networks and collaborations is also relevant to cluster development and innovative performance. A recent study published by the National Bureau of Economic Research demonstrates that large-scale R&D investments during World War II, from Roosevelt's Office of Scientific Research and Development (OSRD), had long-term effects on American invention and industry. Those regions heaviest in OSRD research contracts during the war saw an explosion in patenting in the years after the war, sustained growth in high-tech industry, and far higher employment in associated manufacturing sectors three decades later.²⁴ Federal investments catalyzed a blossoming of "entire local research ecosystems" comprising universities and federally funded research centers.

Along similar modern lines, universities – which rely on federal dollars for most research – are increasingly important influences on the inventive activities of nearby firms²⁵ and on the creation of new startups. Having a ready workforce of skilled science graduates is also important for firm innovation.²⁶ In the case of the NSF ERCs mentioned above, employers have frequently found ERC graduates to be particularly effective research employees.²⁷

Incentive for investment by others. Public research funding and partnerships (as well as R&D tax incentives) can serve as a catalyst for follow-on research investment, in some cases substantial. For instance, studies have found that each \$1 increase of NIH basic research has generated an additional \$8 increase in pharmaceutical R&D,²⁸ while every \$10 million increase for NIH research on a particular disease generates an additional 2.7 additional industry patents in that disease area.²⁹

In the energy space, receiving a Phase I award from the Department of Energy's Small Business Innovation Research (SBIR) program raises the odds of follow-on VC investment by up to 19%, and is associated with increased patenting and revenues.³⁰ And public-private programs like the Manufacturing USA institutes and the ERCs have been effective in eliciting industrial and other partners.

Why is government irreplaceable for all of this?

As mentioned above, industry basic science has increased in certain high-tech sectors. But industry *development* spending has increased even more rapidly. In the *Endless Frontier* era, the federal government was the source of almost two-thirds of all national research and development funding, with industry contributing one-third. Today, the roles are reversed, and industry represents roughly two-thirds of national R&D investments. With this shift toward industrial R&D, is the federal government still vital? The answer is unequivocally yes.

The scientific enterprise has evolved far beyond anything Vannevar Bush imagined in 1945. The vast ecosystem delivers scientific advances, medical cures, innovative technology products, raised standards of living, economic growth, and awe-inspiring understanding of the universe. This ecosystem is nourished by broad and varied federal investment in research and development; university and nonprofit, institute-based scientists driving thought leadership; innovative financial instruments to bring private sector risk capital; entrepreneurs driven to move scientific advances from the lab to the consumer; industry investment, particularly in development; and agile regulatory agencies able to keep up with the progress of science and technology and factor it into decision-making. Each piece of this ecosystem is important, but it all begins with the federal role.

The federal role in research and development also drives the culture of science. This is more important than ever as scientific investment grows around the world, and other nations copy our current model.

The culture of science, human research protections, research integrity, ethics, and diversity (for all its remaining flaws) in the U.S. is hard won – and built upon learning from and correcting many previous mistakes. The U.S. government is the only player in the scientific ecosystem with the heft to ensure that the global culture of science draws from the best of the U.S. enterprise.

For example, openness is a vital ingredient in innovation. The norms of open science are well-established at U.S. universities, and knowledge generated in the academy is able to proliferate through publishing, conferences, and scientist interaction. Collaboration between various kinds of entities – businesses, universities, nonprofit research institutes, and government labs – is a powerful means to innovate. In comparison, most industry R&D is done in-house, and published research from corporate scientists has declined over many years.³¹

In addition, industrial R&D tends to have a built-in bias toward incremental advances and familiar markets rather than breakthroughs or new markets. This is understandable: the profit motive seeks returns, but such returns are highly uncertain when it comes to research investments. Markets seem to have great difficulty valuing research investments in a given firm's portfolio.³² This is particularly true in certain low-innovation sectors, including legacy sectors like energy, which by definition feature substantial obstacles to disruptive innovation.³³ Thus, research expenditures are often the first to be cut when corporate budgets tighten.³⁴

And of course, in addition to the necessities of public research itself, there's also the fact that federally funded research provides a critical training ground for tomorrow's scientists, engineers, innovators, and entrepreneurs.

As VC legend Bill Janeway has written, "The venture capital model is radically unsuited to investment in fundamental science or in technological invention in its nascent stages. For the next generation of entrepreneurs and venture capitalist to have their opportunity to dance, they need government agencies as active and creative as those that served my generation."³⁵

Rising Foreign Investment

Our global competitors understand the value of these investments. They have seen the success of Bush's framework – and have paid it the highest compliment: they are copying it. The 2020 State of U.S. Science and Engineering report – part of the Science and Engineering Indicators released by the National Science Board – indicates that although the U.S. still spent more on R&D than any other country in 2017, other nations are catching up.³⁶ Since 2000, the American share of global R&D has declined from 37% to 25%. China has accounted for nearly a third of the total growth in global R&D in that time, and preliminary data suggest it may have overtaken the U.S. in spending in 2019.

The Benchmarks 2019 report published by the Task Force on American Innovation – to which AAAS contributed – lays out several other metrics in education and other areas reflecting the increasing challenges to U.S. scientific leadership.³⁷

We all know the China story, but it's not just China. Just last week, the United Kingdom released a roadmap for U.K. research and development.³⁸ It's a visionary plan for investing in world-class research, fostering talent, enhancing productivity, and pursuing a place-based approach to ensure all U.K. regions can share in the prosperity. The United States should be answering our own innovation challenges with the same vision and ambition.

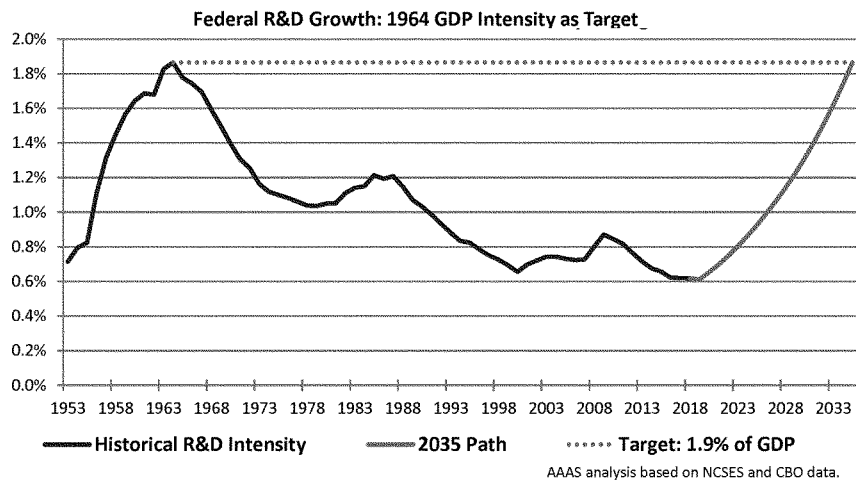
We also face global challenges in the realm of human capital. For instance, based on test scores, U.S. science and mathematics education at the elementary and secondary level is mediocre and stagnant relative to other countries. For decades, the U.S. has relied on foreign-born talent to help meet its S&E job needs. A considerable proportion of U.S. S&E degrees – especially at the doctorate level (34%) – go to international students, many of whom remain in the U.S. after graduating. However, the Indicators data show a troubling shift: foreign student enrollment in U.S. colleges and universities has declined since 2016.³⁹

Internationally mobile students still choose the U.S. more than any other country for their higher education degrees – though the effects of the COVID-19 crises have yet to show up in the data. Students today have more choices than ever before as nations actively court globally mobile talent. The United States' latest actions on legal immigration, combined with the travel restrictions brought about by COVID-19, threaten this key ingredient to our scientific ecosystem.

U.S. Research & Development Investment has stagnated

U.S. research intensity, R&D as a share of GDP, is well below its peak level and below the investment levels of nine other countries. How much should we invest? There is no one right answer to this, but if we're to restore American leadership there are a few different ways to think about the scale of the challenge.

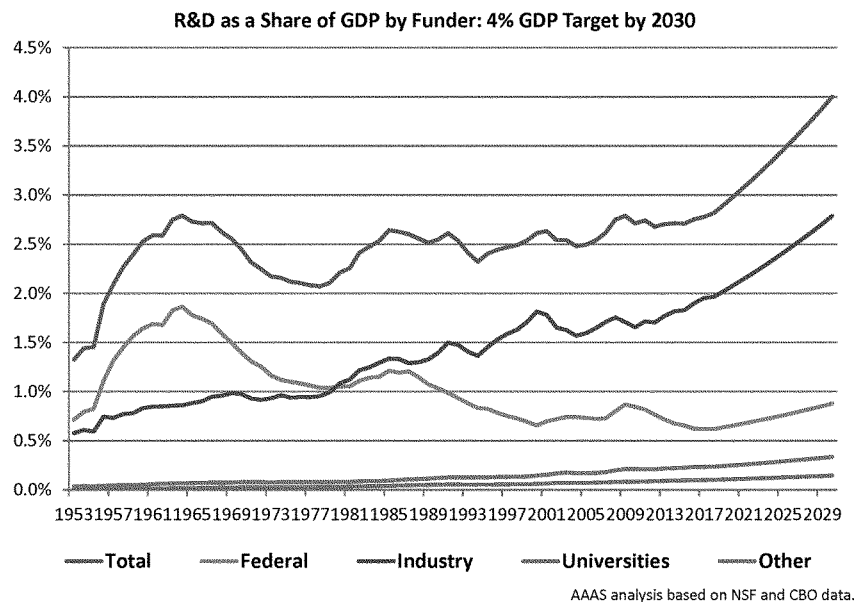
One way is to benchmark us against ourselves. Federal funding for research and development peaked in 1964 at 1.9% of GDP. Let's say you wanted to get the federal government back to this level by 2035. Doing so would require annual increases of about 11% across the enterprise for the next 15 years (see below).



Alternately, we could benchmark the United States against the world. Compared to other OECD countries, the U.S. is just hanging on to the top ten in R&D intensity at about 2.8%, behind Israel, Korea, Germany, Taiwan, and others. That includes all R&D from all sources: public, private, academic, and nonprofit.

Let's say you wanted R&D to hit 4% of U.S. GDP by 2030. This would not put us at the top, but it would get us close – into the top three at least, based on current spending by other global leaders. Assuming funding from all sources were to grow proportionately, federal R&D across all agencies would have to grow by about 7% per year (see below). In addition, we may have to adopt additional policies such as a more generous R&D tax credit to attempt to incent additional investment from other sources. And if those other sources are unable to invest more, that would put additional responsibility on government.

As you can see, regaining American leadership and driving innovation will require substantial investments of public resources – and we'll need sufficient budget space to do it.



CONCLUSIONS

We are living in an era in which science and engineering have delivered extraordinary advances that are improving health, well-being, and economic prosperity for Americans and people around the world – and we are on the cusp of even more life-improving developments and discoveries. Despite some

painful mistakes and errors, the American innovation engine has been the envy of the world. But these successes are lagging indicators of legislative, policy, and investment choices made over the last 75 years. Continued success is not guaranteed, but our past willingness to take on risks has shown a high rate of return. Our generation must make wise policy decisions and investment choices now to deliver on continued well-being and economic growth for the next generation.

RECOMMENDATIONS

- 1) The United States should update the Vannevar Bush framework for advancing science and serving society with an emphasis on full spectrum innovation: including fundamental science, mission-driven technology, and useful knowledge programs that meet local, national, and international needs, with the federal government as a key partner. We shouldn't be afraid to experiment with different ways of funding R&D through different models and networks to meet societal goals, whether it's traditional single-investigator project grants, or people-centered grants, or teams and hubs, or prizes, or other models. The framework should include guidance for how the federal government should coordinate science in response to crises.
- 2) Under this new framework, the United States should increase federal investment in R&D as a percentage of GDP to 1.9%, requiring increases of approximately 11% per year. This would match the peak we achieved more than five decades ago and put us firmly back into the top three countries for research intensity globally.
- 3) Scientific leaders must ensure that the scientific enterprise is supporting opportunities for all by addressing challenges within the scientific enterprise and by providing the evidence base to inform national policymaking. This is critical to ensuring a fairer scientific enterprise and a fairer world.

In closing, thank you for this opportunity to address the value and importance of federal R&D.

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Chairman YARMUTH. Thank you very much for your testimony. I now recognize Dr. Romer for five minutes. Please unmute your mic, Dr. Romer.

STATEMENT OF PAUL ROMER, PH.D.

Dr. ROMER. Chairman Yarmuth, Ranking Member Womack, and Members of the Committee, thank you for giving me this chance to contribute to this discussion about how to fuel innovation and recovery and to contribute by summarizing the lessons I have learned from my analysis of long-run economic growth.

We share two ambitions: We want the United States to be the leading nation in basic scientific research. We also want it to be the leading nation in the delivery of the technological progress that lifts the productivity of our work force and raises standards of living for our citizens.

The main message I want to convey today is that it takes different types of investment to achieve these two ambitions. As a result, you, the Members of Congress, face a tradeoff. When you contemplate additional investment in our future, you can choose to invest in basic science or in technological progress.

The secondary message that I want convey is that, in my opinion, in recent decades, the nation has underinvested in technological progress. In particular, we have allowed the strengths that we built up prior to World War II to depreciate. So, as a result, the investments you could make now that would yield the highest payoffs would be investments in the kinds of measures that delivered such remarkable technological progress before World War II.

If I could ask for the first of my slides to be displayed.

[Slide.]

Leader

Follower

**Basic Scientific
Achievement**

Follower Leader


Technological Progress

This two-by-two table suggests that nations can be either leaders or followers in basic scientific achievement or in technological progress and that a nation can be a leader in one or the other or both.

If I could have the second slide.

[Slide.]

**Basic Scientific
Achievement**

Leader	US today	 US after WWII
Follower		

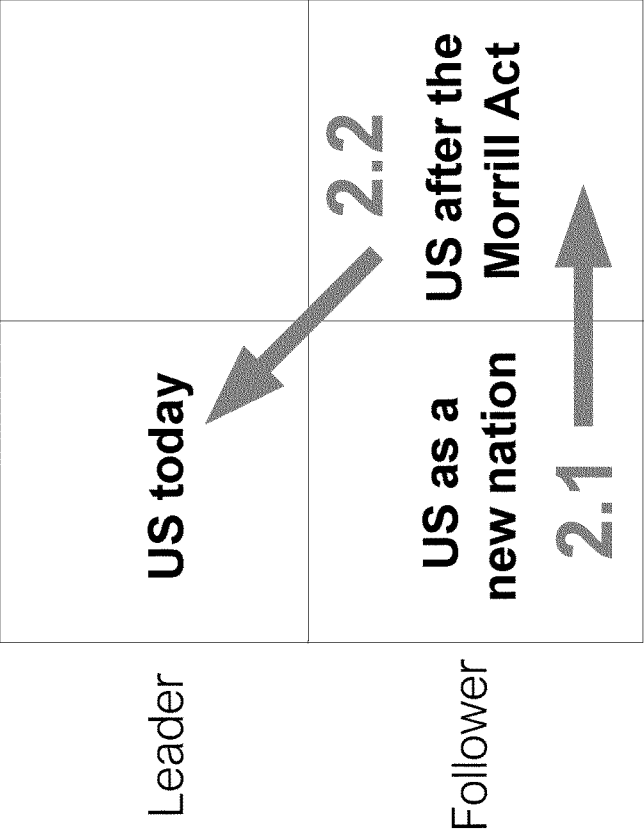
Follower Leader

Technological Progress

The narrative that is often told about the United States is that we were in a position of leadership along both dimensions after World War II but, because of changes in the environment, changes in the economy, other changes, we are no longer as good at delivering technological progress. In the language that Deborah Wince-Smith will use, we generate ideas, but they don't cross the valley of death into the realm where they deliver practical benefit.

If I could have the next slide.

[Slide.]



Basic Scientific Achievement

Follower Leader

Technological Progress

The story I want to tell of our history is slightly different. We started out, as a nation, as a follower in both science and in technology, but because of the Morrill Act and our investment in the land-grant institutions, including the institution that Ranking Member Womack mentioned in Arkansas—because of our investment in the land-grant universities, we moved into a position of technological dominance prior to World War II.

Then, after World War II, we achieved a huge transformation where we became the world's leading producer of basic scientific research. But this was a new endeavor for us. We were not a nation that produced Nobel Prize-quality research before World War II. And, unfortunately, in this transition, we lost the strengths, we didn't continue to invest in the strengths of our system that existed before.

Now, the extent of the problem that this leaves us with, whether you believe in the first narrative or the second one, was brought home to me by a conversation with Kari Stefansson, who is the founder of deCODE genetics, the company that is doing population-scale genetics in Iceland and which was the leader in its testing program to combat the pandemic.

Kari said to me, Paul, all of the insights, all of the science that we rely on and every country in the world relies on was developed in U.S. universities, but why is it that your nation is not taking the same advantage of those developments?

This suggests that our problem with technology and transfer of knowledge is not exclusively one that exists in the business sector; we see it in the government sector as well. And we need to invest in the mechanisms that once worked, that made us a powerhouse in technological progression, and could do so again.

Thank you.

[The prepared statement of Paul Romer follows:]

***What It Takes To Be a Leader in Both Basic
Science and Technological Progress***

PAUL ROMER

New York University

Statement for House Budget Committee Hearing on Federal R&D

July 8, 2020

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1 The Weakness Revealed By the Pandemic

In a conversation about testing for the SARS-Cov-2 virus, Kari Stefansson, the founder of deCode Genetics, the firm that has been doing population scale genomics in Iceland and which turned its attention to monitoring the spread of the virus, said to me that the technology that every country in the world is now using to identify the presence of the virus was developed in universities based in the US. The puzzle was why the US has been less effective than other countries in taking practical advantage of its basic scientific advances and using them to control the pandemic.

It is a good question. In 2019, a team at Johns Hopkins evaluated how well prepared various nations were to manage a pandemic. They concluded that the United States was the best prepared nation in the world. The United Kingdom was number two. (The results are available at <https://www.ghsindex.org/>.)

So the question is not simply why the US response was so inadequate, but also why the people tasked with thinking about these issues failed to anticipate how poorly we would do.

For members of the academic community, the convenient answer to this question is that blame for our failed national response lies with our political leaders. But as the warning sign at rail crossing in France cautions: Be careful. One train may hide another.

2 Science, Technology, and That Trade-Off Thing

In the wake of the pandemic, we need to revisit the conversation about the failure of our national innovation system to apply scientific insights and capture the practical benefits we desire. The usual frame for this discussion posits a private business sector that "failed to take up" the insights discovered by the academic scientists.

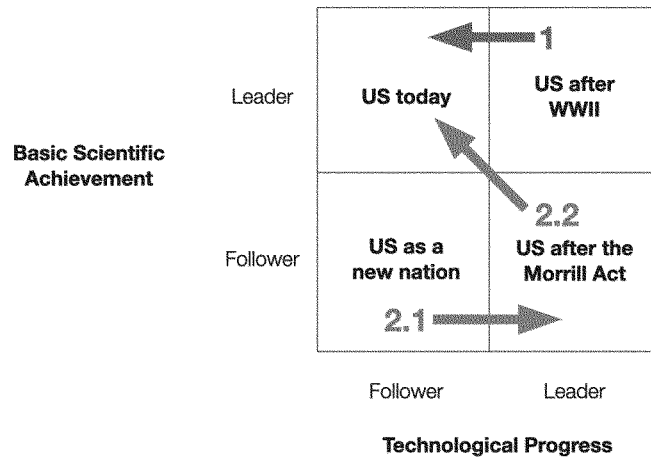


Figure 1: Two narratives about the United States

In the current iteration of this discussion, we need to consider, skeptically, a new version of this narrative in which academics claim that it was the government that “failed to take up” the academic insights.

Many commentators have observed that national leadership in basic science is neither necessary nor sufficient for leadership in technological progress. In terms of the two-by-two table in Figure 1, this means that a nation can end up in either of the off-diagonal boxes.

There is, of course, general agreement that the United States should aspire to leadership along both dimensions and a lingering presumption that leadership in science should naturally translate into leadership in technology. In his famous report *The Endless Frontier*, Vannevar Bush laid out what has come to be known as the “linear model” in which new ideas are produced by basic science, refined by applied science, and translated in practical benefits by product development. According

to this model, the rate of new discoveries is limited by the rate of new ideas from basic science which puts new possibilities onto its conveyor belt. Were this model correct, leadership in basic science would be necessary for leadership in technology but not sufficient. The downstream activities are also required. This helps explain the defense by basic scientists, that others have not "taken up" their insights. The problem lies downstream.

There are instances of discovery that support the linear model. Basic mathematical research in number theory translated into applied cryptography. But there are many other instances which do not. The basic science of thermodynamics did not lead to the steam engine as an application. The steam engine lead to thermodynamics as physicists tried to figure out what it was that the problem solvers were doing. As a result, no student of science and technology is willing to defend the linear model.

The historical evidence also undermines the linear model. Nations do find themselves in the off-diagonal boxes, leading in one dimension but not the other. At different points in time, the United States has found itself in both off-diagonal boxes. More controversially, I want to suggest that we may not ever have been in a stable position of dual leadership in the box in the upper right.

There is a narrative about the current state in the US that is informed by the linear model which starts in the post-WWII era, one suggested by the red arrow and the number 1 in Figure 1. According to this narrative, the US was a leader along both dimensions, but that something went wrong in the downstream processes.

But to tell the full story of the United States, we need to go back to the 18th century, when this country was a follower along both dimensions. The pivotal change came with the passage of the Morrill Act of 1862, which established the principle of having a land grant university in every state. The second pivot comes after WWII, is marked by Bush's report. The driving force in this new era was a

dramatic expansion of Federal support for basic scientific research and a turn away from the mandate of the Morrill Act: "to teach such branches of learning as are related to agriculture and the mechanic arts, in such manner as the legislatures of the States may respectively prescribe." The post-WWII system was a shift from teaching to research, from problem solving to fundamental inquiry, and state to federal control. To illustrate this practical focus, my late Stanford colleague, Nathan Rosenberg, used to remind his students that the football team at Purdue is known as the Boilermakers because students in its engineering school did research on a fully operational steam locomotive railroad engine kept at the school in the 1890s. Another example that Nate used to emphasize the role of local control over the lines of inquiry at the land grant schools was the development by researchers at the University of Minnesota of the pelletization process that was essential for full exploitation of the state's iron ore deposits.

The possibility suggested in the figure by the blue arrows labeled with the number 2 is that the story of the US after WWII may best be understood as a traverse from the box in the lower right to the box in the upper left, along which, for a period of time, we continued to take advantage of our capital in delivering technological progress without recognizing that it was depreciating.

Another of Nate's revealing illustrations of the sharp change in our national innovation system after WWII comes from Chemistry. In the first few decades of twentieth century, scientists working in the US received almost no Nobel prizes. In Chemistry, the leading nations were Germany and the UK. But it was in this era that the United States moved into a position of worldwide dominance of the petrochemical industry. Moreover, it is not hard to understand how the US was so successful. Our practically oriented universities, which focused on their educational mission, introduced a new discipline, chemical engineering, that was taught in a new type of professional school.

So for me, the story of the US in the last 120 years is the story of the traverse from technological leadership to scientific leadership. From this perspective, the challenge now is not to invent a new strategy for being the worldwide technological leader. It is to revive the strategy that worked before, and in so doing, to find a better balance between the policies that foster basic scientific leadership and the ones that encourage technological leadership. This nation can do both, but it will not do both if the advocates for basic science always get their way in any policy decision.

In uncharted seas, maps once warned "Here, there be dragons." Figure 1 warns that "Here, there be tradeoffs."

3 Listening to Other Voices

There are many details behind the suggestions that I will outline. To keep my remarks short, I summarize very briefly two papers that I wrote on how to restore some of the advantageous features of our pre-WWII national innovation system. Then in the final section, I will offer three general principles that can guide other changes we could make.

The two papers, which are attached as Appendix A and B, try to create mechanisms that will feed insights from industrial users of technology and from aspiring students of science and engineering into the decisions on university campuses. Their insights should supplement the insights provided by the successful scientists who dominate in a system where universities compete for research funds provided by the federal government. Before those well-established scientist crank up their habitual attack on "meddling by outsiders," let me be clear that in these two papers, I do not suggest any encroachment on their domain of influence, nor any reduction in the funds that receive from the federal government. All I suggest is that we provide financial support to universities in some additional ways.

The way I propose for giving an industry some influence over decisions made on campus is to give it the power to levy a tax on all firms in the industry and to use the proceeds to support research and educational programs that will benefit the industry. The corresponding way to give students a voice is to bring back the system that prevailed before WWII, in which students who paid tuition could decide where they studied and what they studied. Under this system, universities competed for tuition revenue by introducing such new courses of study as chemical and electrical engineering. The way to do this today and simultaneously to encourage more US citizens who pursue a graduate education is for the federal government to create a large number of portable fellowships that are rewarded to the most talented undergraduates. These fellowships should cover both living expenses and generous tuition charges for three full years of graduate education. The fellowships should be portable in the sense that a recipient could use it to pursue any degree program in science and engineering at any university.

I know from the discussions that followed my paper on portable fellowships, which included discussions with staff and members of Congress that led to the introduction of a bill that provided for these fellowships, that the leading research universities and the advocates for basic science opposed this new additional source of funding. This is why I suggested before that the right decision for the nation might mean that the advocates for basic science do not get their way. The National Defense Education Act (NDEA), passed in 1958, created a fellowship program that was similar in spirit to the one I propose. Over time, that program was replaced by one that the professors in research universities, as the principle investigators on research grants, preferred. Instead of giving funds directly to students and letting them make their own decisions, the funding agencies gave money to professors, who supported graduate students by hiring them to work on the research projects that the professors wanted to work on. I am not persuaded, but a reasonable person could

claim that the shift to unilateral control by principle investigators is the best way to support basic science. But what cannot be denied is that giving the professors unilateral control deprived aspiring scientists and engineers, many of whom would end up working in industry, of any say in the graduate educational programs that they could pursue on the nation's university campuses. It deprived the nation of the type of educational innovation that led to the creation of schools of chemical engineering.

Even if the Congress comes up with new money to provide the type of fellowships I propose that empower aspiring scientists and engineers, even if the Congress holds constant the funds that agencies can give as research grants to professors, I can assure you that the leaders of the scientific community, who are based in a few dominant research institutions, will not welcome these new fellowships. My message to them: "There be tradeoffs here." What is best for you may not be best for the nation.

4 General Principles

I will close by offering some general principles that could help guide us back toward leadership in both basic science achievement and in technological progress, back toward a system that is a hybrid between the one that brought the US to worldwide preeminence in industrial technology before WWII and the one that displaced when the federal government took control and gave so much autonomy to professors.

The first is a general principle that I inferred after my first inquiries into science and technology policy. The next two are more recent. They reflect the lessons I learned from the failure of our regulatory system in the run-up to the financial crisis. (In Appendix C, I attach a third paper prompted by the financial crisis.) These last two have, to my surprise, been reinforced by the failures that are now evident in our failed response to the pandemic.

4.1 People are what matter, not papers or patents

The most important outputs produced by the nations universities are well trained people. People working in many different organizations can write papers and apply for patents. The unique contribution that universities can make to the nation is to give the most talented young people a chance to acquire the skills, the confidence, the habits of mind that will allow some of them to make outstanding contributions either to basic science or to technological progress, or to both. The Morrill Act and the NDEA rewarded universities for making these investments in people. Today, we should look for new ways to reward these investments once again and we should make sure that the educational programs offered by universities respond to the opportunities that students perceive.

4.2 Achieve robustness via competition

Part of the genius of the Morrill Act is that it did not try to create a world beating national university. It build a system of many different competing universities. After the introduction of the centralized federal role in WWII, this has evolved toward one dominated by a handful of winners. The NDEA included a system for allocating its fellowships that prevented the leaders of the day from growing stronger at the expense of the followers. In effect, the NDEA fellowship program included a competition policy that kept a few powerful institutions from dominating the national innovation system.

We should copy this feature of the NDEA fellowship program in any new system that supports universities. And we should extend the insight that motivated this approach and the design implicit in the Morrill Act. We should rely on the states. We should encourage many voices. One of the problems that we now see with the federal system for protecting health is that it gave monopoly powers to the FDA and

the CDC. In so doing, we created what the engineers call single points of failure in our defense against viral pathogens. Instead of further concentrating power in these dominant agencies, we should have the courage to bet on the states as the Morrill Act did, to build up stronger departments of health in each of the states and defer to the states on such critical decisions as what types of tests to deploy for identifying a dangerous viral pathogen.

If we can trust state governments to run universities, we can trust them to regulate tests.

4.3 Protect scientific integrity by separating the roles of decision-maker and fact-finder

One of the most useful and under-appreciated innovations in the US system of governance is the division of labor between the FAA, which makes regulatory decisions about aviation, and the National Transportation Safety Board, which is responsible for establishing the facts after any accident.

There is an inevitable tendency for an agency that has to make technical decisions to report to the public a version of the facts that supports its decisions. These agencies turn into advocates for specific positions. In the process, they lose their scientific objectivity. During this pandemic, we have seen several important instances where agencies that were responsible for difficult real-time decisions that were central to our pandemic response – the CDC, the FDA, and the WHO – justified their decisions by presenting the public with a biased or misleading summary of the facts.

There are now four important questions on which informed observers now question the factual answers provided by these agencies:

1. Do masks limit the spread of the virus? 2. Do people who are infected by the SARS-CoV-2 virus but do not currently show symptoms cause a substantial

fraction of its transmission? 3. Does the virus spread through the air mainly via large droplets or also through smaller aerosol particles? 4. Does a policy of testing for the virus and isolating those who test positive reduce the spread of the virus?

I will not try to summarize the evidence that bears on these four questions. Nor will I try second guess the policy decisions by these agencies that were tied to the answers they provided to these four questions.

However, as someone who has spent a great deal of time trying to understand the facts and the positions taken by the different parties in the debates about the facts, I will report that there are credible scientists who now have grave concerns about the scientific integrity of the messages that these agencies have conveyed to the public.

The risk here is not just that a biased reading of the facts will lead to bad decisions or hinder reconsideration of those decisions as new evidence comes in. The far more troubling concern is that well informed people have stopped believing the assertions of fact that these agencies make and that their skepticism is fueling a broader distrust of authority by those who are not as well informed.

To make progress, we have to base our decisions on the facts. If voters do not trust scientific authorities, our democracy will not be able to base our public policy decisions on the facts.

There are many possible ways to divide up the responsibility for making decisions about public health between states and the Federal government. And many possible places where we could assign to some other, independent agency the role of finder of fact. What would not make sense is to create many different copies of the CDC or the FDA at the state level, each of which continues to have conflicting responsibilities to make decisions and provide a clear statement of an evolving pattern of facts to the public.

5 Appendix A

Implementing a National Technology Strategy with Self-Organizing Industry Investment Boards (Brookings Papers on Economic Activity, 1993, No. 2)

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Canadian Institute for Advanced Research

Implementing a National Technology Strategy with Self-Organizing Industry Investment Boards

THE MOST IMPORTANT LESSON from the study of research and development, economic growth, and the history of technology is that there are more ways to arrange the objects of the physical world than humans can possibly imagine. Ultimately, all increases in standards of living can be traced to discoveries of more valuable arrangements for the things in the earth's crust and atmosphere. The personal computer that I used to write this paper is made from almost exactly the same physical materials as the PC that I bought ten years ago—about thirty pounds of steel, copper, aluminum, plastic, and silicon, with bits of gold, iron oxide, and miscellaneous other elements mixed in. In my new PC these materials are arranged in a slightly different way that makes them about fifty times more useful than they were in the original configuration.

No amount of savings and investment, no policy of macroeconomic fine-tuning, no set of tax and spending incentives can generate sustained economic growth unless it is accompanied by the countless large and small discoveries that are required to create more value from a fixed set of natural resources. These discoveries are the product of a complicated set of market and nonmarket institutions that constitute what has been called a national innovation system. This paper considers both the economic

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opportunities and the political risks inherent in attempts to strengthen this system. It proposes an institutional arrangement that could provide more financial support for innovative activity and direct it toward areas with large economic payoffs.

Even more impressive than the availability of a much faster PC to do word processing is the fact that my family drinks milk from a cow. If the milk cow did not exist, no one would ever believe that carbon, oxygen, hydrogen, and a few other types of atoms could possibly be assembled into a chemical refinery that automatically converts grass, water, and air into a nearly perfect liquid protein dietary supplement. This refinery operates with almost no human supervision, is mobile so it can search out its own inputs, can heal most mechanical failures, and can detect and neutralize any microscopic pathogens that enter the system. It even makes more than milk. It can build several replacement factories out of the same raw materials: grass, water, and air.

Compared with the cow, my PC has all the sophistication of a Tinkertoy. And if the particular arrangement of atoms that make a cow can come together through a blind process of mutation and selection—nature’s version of trial and error—imagine how many other ways atoms can be arranged that are as astonishing and valuable as a microprocessor and a cow. The fundamental challenge in economic growth is to find these new arrangements.

This optimistic potential for exploiting what Vannevar Bush called “the endless frontier” of scientific and technological opportunity is limited only by the difficulty of organizing collective action.¹ It takes collective action to encourage discovery and sustain the free flow of ideas, and the political mechanisms used to undertake collective action suffer from serious inherent defects.

But people create new institutions, just as they discover new technologies. Policy innovators discover better ways to undertake collective action, just as scientists, engineers, and product designers discover better ways to arrange physical objects. Vannevar Bush did more than write a report about the endless frontier of science. He midwived the birth of the National Science Foundation and peer-reviewed research grants for basic research at universities. He identified an important opportunity for collec-

1. Bush (1945).

tive action and then constructed an institutional arrangement to exploit this opportunity at minimal political cost.

Any contemporary discussion of a national technology strategy should be based on a balanced assessment of the potential benefits from collective action to spur growth and the risks inherent in undertaking collective action through the political process. Even die-hard free marketeers should concede that there is an opportunity for collective action to support some forms of basic research. On the other side, even the most ardent advocate of an activist government must admit that the nation's fifty-year experiment with an explicit industrial policy for the savings and loan industry shows how badly awry well-intentioned collective action can go when it is implemented through the existing political institutions.

Once the tension between the large opportunities for benefiting from collective action and limited political and institutional capabilities for undertaking effective collective action is recognized, it becomes clear that innovation in institutional mechanisms could be very valuable. Surely, the opportunity to experiment with new institutions is as great as the opportunity to experiment with new arrangements of physical objects. The standard dichotomy in economic policy debates—market exchange versus government intervention—does not capture the complexity of the kinds of social institutions already used to achieve common goals. It also fails to suggest the broad range of new institutional arrangements that could be tried. In its purest form the market is a mechanism for allowing independent action by all individuals, with no explicit coordination. The government is a mechanism for explicitly coordinating the actions of all people. Most economic activity is supported by institutional arrangements that are intermediate between these extremes.

After all, the modern capitalist economy is organized neither as a market nor as a government. It lets large numbers of people exploit the benefits of collective action through explicit, hierarchical coordination as members of a corporation, and in this sense large parts of a capitalist economy function like a government. But an economy with many firms subjects each to the discipline of competition, so in this sense the economy is organized more like a market. The diverse population of corporations is constantly changing, constantly finding new and different ways for large groups of people to work toward some collective end. Some corporations find new ways to structure themselves. Others die off and are replaced by

new and better arrangements. What a national innovation system needs is something like this kind of dynamic, something that lets us take advantage of mutually beneficial coordinated action and that uses the pressures of *competition and a market test to shut down ineffective institutional arrangements* and to reward promising ones.

To show how such a process might work, I describe a specific policy proposal conceived with this end in mind. Whatever the final judgment is on this particular proposal, the general analytical point will, I hope, be clear. To encourage technical change, it is not enough to call on business leaders to be more innovative. Policymakers must themselves be willing to experiment with new institutional arrangements.

Self-Organizing Industry Investment Boards

This proposal specifies a process, not a specific policy. To see how it would work, consider a hypothetical example. Suppose you run the Acme Widget company and I run Consolidated Widgets. You and I and many other widget makers come together and decide that there are industry-wide opportunities and problems that independent action by individual firms cannot address. You think, for example, that university professors could be doing useful research on questions about the basic principles of widget design and manufacturing if they just had the funds and the incentive to do so. I believe that the upstream industry that manufactures widget-making equipment could be designing more useful specialized equipment.

Under the proposal outlined in this paper, widget makers could take collective action on these matters by following the steps specified in a general piece of enabling legislation. They would start by petitioning the secretary of commerce, giving the argument for provision of an industry-specific public good. The secretary would then hold a hearing to certify that the proposal for collective action addresses a genuine public need. If the proposal passes this test, an election would be held in which all widget manufacturers vote whether to levy, say, a 1 percent tax on widget sales. If a large enough fraction of the industry (measured as a fraction of total sales, as a fraction of the total number of firms, or some combination of the two) votes in favor of this initiative, a tax

backed by the full force of law would be imposed on the entire industry. The proceeds from the tax would not, however, go to the government.

Part of the presentation to the secretary of commerce and then to the industry would outline plans for creating industry investment boards. You will take the initiative to organize an investment board that will fund university-based widget research. I will organize a board that supports the development of widget-making machinery in the upstream industry. Both of these boards will function as pass-throughs, accepting tax obligations from contributing firms and using these funds to support research in universities in the first case or development in upstream firms in the second. After the tax is passed, the two boards would solicit the tax funds from the firms in the industry. Suppose that your firm has sales of \$100 million a year, so it has to decide where to allocate its \$1 million in annual tax obligations. Because you are organizing the "University Research Board," you might decide to allocate all of the \$1 million to it. My firm has sales of \$200 million a year. I might decide to have my firm split its \$2 million tax obligation, giving \$1 million to the "Upstream Equipment Development Board" that I help organize and \$1 million to the University Research Board. Each year the leaders of other firms would have to decide how to allocate their tax obligations between these two boards and any others that might be created. The amount they have to contribute is fixed by their sales and the tax rate. They are free, nevertheless, to decide which board receives their contributions. If they do not approve of the boards that exist, they are free to start a new one.

Each industry board would have a board of directors answerable to its contributing firms and would operate as a private, nonprofit foundation. The boards would be limited by the general terms of the enabling legislation but would otherwise have wide latitude to make decisions without any direct oversight or second-guessing by the executive, legislative, or judicial branches of government. A general limitation would require each board to invest only in common property resources that benefit the entire industry. For example, all specialized equipment developed by the Upstream Equipment Development Board in collaboration with the upstream industry would be available for sale to all widget-making firms on equal terms. All research funded by the University Research Board would be freely distributed in the tradition of open university-based science. Thus, neither board could fund research or

equipment development that would be conducted in-house by a firm in the widget industry. All of the activities of the boards would have to be made public.

The enabling legislation should also specify that absolutely no tax funds could be used to support lobbying, public relations, or any kind of political activity. Also, no direct or indirect kickbacks or side payments to firms in the industry would be permitted. The tax rate used in each industry could vary, but a maximum tax, on the order of 2 percent of sales, would need to be specified in the enabling legislation. The legislation should also articulate the general principle that the tax should be a domestic consumption tax rather than a production tax. Units produced domestically for sale abroad would not be subject to the tax, but units produced abroad and sold domestically would. The legislation would also mandate equal treatment for all firms. Foreign firms would vote in the referendum, pay tax on their sales in the United States, allocate their tax obligations, and participate in the governance of the board or boards they support, in exactly the same fashion as domestic firms.

Suppose that other industry leaders come to believe that the most important problem facing the industry is an inadequate supply of post-graduate engineers with special training in widget-related design issues. Or suppose they decide that the most important investment would be to disseminate existing information about the principles of manufacturing to widget-making firms. Other firms might decide that junior college training of basic skills for current and future workers in the industry is the most important priority. An interested firm or group of firms could, at any time, petition the secretary of commerce, participate in public hearings, and then establish a Ph.D. Engineering Fellowship Board, an Extension and Diffusion Board, or a Worker Training Board. These new boards would compete with existing boards for the tax obligations of the different firms in the industry.

Over time, if contributing firms felt that the University Research Board was funding an incestuous network of scientists doing research of limited value to the industry, a competing research board could come into existence, or the funding firms could simply vote with their feet and take their tax dollars to other boards. In the worst case, if none of the boards were doing work that justified the cost, firms could use a periodically scheduled election to rescind the tax altogether.

The original proposal to the secretary of commerce would have to specify how the tax would be administered. Some boundary would have to be established, for example, between true widgets, which would be taxed, and near-widgets, which would not. An overall industry association, financed from an expressly limited share of total industry tax revenue, would have to be created to administer the tax system and perform the basic audit and information collection activities necessary to monitor compliance. Cases of explicit fraud or intentional noncompliance could be referred to an appropriate government agency with the power to impose fines, compel testimony, and, if necessary, undertake prosecution.

Precedents

This proposal may sound like political science fiction, but it is modeled on arrangements that already exist. The closest precedent is specified in the Agricultural Marketing Agreement Act of 1937, which outlines procedures for establishing arrangements called marketing orders.² Growers of a particular agricultural commodity can petition the secretary of agriculture to establish a market order on their behalf. Typically, the market order is approved if either two-thirds of the growers or growers representing two-thirds of output by volume support the proposal in the subsequent referendum. A new referendum is usually held every six years to gauge grower support. At any time, the secretary of agriculture can suspend any marketing order that is not operating in accordance with the aims of the enabling legislation.

Marketing orders designed to support research and development (R&D) and market promotion activities differ from the proposal in this paper only in that the funds raised by the tax automatically go to a single marketing board. There is no element of competition between boards and no free entry.

About three-quarters of the marketing orders in agriculture collect funds for research, development, and market promotion. (This is how the popular California raisin advertisements were financed, for example.) Marketing orders can also specify package and container regula-

2. Powers (1990).

tions, or size and grade regulations. These kinds of activities should be sharply distinguished from the notorious volume control regulations (that is, output restrictions) imposed in about half of all agricultural marketing orders. Quantity restrictions are clearly an activity that no economist would want to encourage, and they should not be tolerated, much less encouraged, in legislation that specifies the acceptable activities for the investment boards contemplated here.

This proposal has other, less obvious parallels with existing arrangements. For example, many (but not all) public electrical utilities contribute to the Electric Power Research Institute (EPRI), which finances research on a variety of industry-related matters. If local regulators let contributions to EPRI count as part of cost in figuring the utility's rate base, they are, in effect, using a government-sanctioned tax on electricity to support industry-related research. Just as in agriculture, however, there are no alternative research boards. Some observers maintain that EPRI may not be as effective in stimulating research as it once was or as it could be, perhaps because it faces no competition.

Before the breakup of the Bell System, Bell Labs was supported in a similar fashion. Each of the operating companies paid a few percent of total revenues to AT&T, which supported Bell Labs out of the proceeds. Again, to the extent that this contribution was built into the rate base that utility regulators allowed the operating companies, it amounted to a government-sanctioned tax used for industry-related research purposes. Because AT&T controlled the vast majority of telephone operating companies, free riding was not a problem.

Most observers judge Bell Labs to have been an extremely effective research organization. It made fundamental contributions to basic science. Information theory was created there. Radio astronomy was invented there. The background radiation that is the best evidence available for the "big bang" was discovered there. Bell Labs also produced high-quality scientific discoveries that have had enormous practical and commercial implications: the transistor, the laser, fiber optic transmission of information, and Unix, the first major computer operating system to run on computers made by many different manufacturers.

As evidence that firms can come together and take actions that are in the interest of the industry as a whole, one need look no further than the pharmaceutical industry. It recently persuaded the Food and Drug Administration (FDA) to raise the fees it levies when a company sub-

mits a drug for approval. The explicit understanding was that the FDA would use the additional revenue from this fee to hire more evaluators so that the agency could reduce the time it takes to reach a decision on drug approval.

The Economic Opportunities for Collective Action

It takes two arguments to make a case for this proposal. I must show why there are any important unexploited economic gains that require collective action. Then I must compare the potential gains with the political risks of implementing the system. This section outlines the theoretical argument for large potential gains from collective action. The next refers to evidence on their quantitative importance. Subsequent sections take up the political risks of this and other forms of technology policy.

If physical objects were the only economic goods, there would be little opportunity for collective action beyond the universally recognized need to establish a system of property rights. But as table 1 suggests, objects are not the only economic goods. They are not even the most important goods. The table presents a two-way classification of different kinds of economic goods. The left and right columns classify goods according to their costs of production. The horizontal dimension classifies them by the strength of the property rights available for each good.

The column on the left lists physical objects that are consumed directly or that provide services that are consumed. These kinds of things—land, fish, a worker's labor effort—are typically thought of as economic goods. The column on the right lists goods that can be represented as bit strings. They are all examples of information in the mathematical sense of the term. Whether it is literally a bit string (such as computer code or a digital musical recording) or is something represented in words or symbols that could be converted into bit strings (the design for a microprocessor, the operations manual for Wal-Mart stores, or the results of scientific investigation), any good in this column is a piece of pure information.

The technical terms from public finance for the types of goods in the two columns are rival goods and nonrival goods. The objects are rival

Table 1. Economic Attributes of Various Goods

<i>Degree of control (percent)</i>	<i>Rival goods (objects)</i>	<i>Nonrival goods (bit strings)</i>
100	Private goods: for example, a piece of unimproved land	An encoded satellite television broadcast
	A car	A digital music recording The design for a microprocessor Computer code The operations manual for Wal-Mart stores
	A worker's labor effort	General principles of chemical engineering Principles behind window-based graphical user interfaces The do-loop in computer programming
	Fish in the sea Clean air	
0	Sterile insects used for pest control	Public goods: for example, basic research in physics

goods because you and I are rivals for their use. You can eat the fish or I can, but not both of us. A bit string is a nonrival good because once it has been produced, we are not rivals for its use. I can listen to the musical recording or take advantage of the software code without in any way diminishing its usefulness to you or anyone else.

The most important result of the work on "endogenous growth" during the last ten years has been the renewed attention devoted to these attributes of ideas as economic goods. The first conclusion that emerges from the theory of growth was clear even in neoclassical models: it is the production of nonrival goods that makes growth possible. The second conclusion, which has emerged only after a great deal of work, is that the usual invisible hand result applies only to an artificial economy in which nonrival goods are provided exogenously by nature. In a real economy, an inherent, unavoidable conflict exists between the incentives necessary to encourage the production of these goods and the

incentives that lead to the optimal distribution of these goods, both to users and to the developers of other related nonrival goods. This means that private property rights and market exchange are not the perfect institutions for supporting growth. In fact, no simple description of the perfect institutional arrangement can exist. In any particular context, one must explicitly address the trade-offs both between the incentives for discovery and those for diffusion and between the limitations of market mechanisms and those of political mechanisms.

The two columns in the table correspond roughly to the distinction emphasized in the introduction between physical objects and intangible discoveries about new ways to arrange those objects. Farming, resource extraction, manufacturing, and distribution are all examples of actions that transform physical objects. For most people, these are the kinds of things that first come to mind when they think of economic activity. Discovery, in contrast, is how new, nonrival instructions are found for using rival goods more creatively. As the introduction suggests, discovery is where the real action is in economic life. Because nonrival goods are intangible, they are hard to measure. Moreover, they typically affect the economy in small increments that are hard to perceive from one year to the next. (The computer industry, where dramatic change can be seen in real time, is a notable exception.) But one needs to read only a little history to appreciate the profound cumulative effect of these nonrival goods—these discoveries—in almost all areas of economic activity. If the Earth were returned to the physical state that existed ten thousand years ago, wiping out all structures, physical capital, and civil engineering projects, but the total stock of accumulated knowledge were retained (in an exempted library where books and other records were kept), current standards of living would be recovered within a few generations. If the experiment were reversed, with the physical state of the world retained but the state of knowledge returned to what it was ten thousand years ago, our economic prospects would be much bleaker.

The sharp distinction that the table draws between rival and nonrival goods is rarely apparent in practice because real goods are almost always a mixture of the two. If you buy shrink-wrapped software, for example, you purchase a bundle that consists of rival objects (some floppy disks and a book) and a nonrival good (the legal right to use the bit string that encodes the computer program). The distinction between

an object such as a floppy disk and an intangible such as the computer code stored on the disk is important because it points to a fundamental difference in the associated costs of production. The cost of producing the computer code is virtually all fixed cost, or “first copy” cost. Firms spend millions (sometimes hundreds of millions) of dollars finding just the right bit string, but once they have it, they can replicate it at essentially zero cost. Once a nonrival good is produced, it is a good with no opportunity cost. The cost of the floppy disk, in contrast, is almost entirely the constant cost of producing additional disks; almost, but not quite, because, of course, the floppy disk itself reflects a sophisticated design that required an important fixed-cost investment. The floppy disk is not a pure rival good, but unimproved land is, because it has no underlying design cost.

In contrast to the horizontal distinction between rival and nonrival goods, the vertical dimension in the table reflects the more familiar issue of property rights, appropriability, excludability, or, simply, control. It is possible to control different kinds of goods by maintaining physical possession, perhaps with the assistance of the legal system, or by keeping some valuable piece of information secret. Land is placed relatively high up in its column because it is rarely stolen and because the cost of maintaining control over land is small compared with its market value. An automobile is lower down the column, because cars are more frequently stolen and the total resources spent by society on maintaining control over cars is higher. Goods that are both object-like (that is, rival) and over which almost perfect control can be maintained are called private goods. Land is a private good, and a car is close enough for most analytical purposes.

Farther down the rival goods column are examples of objects (or services from objects) for which property rights are weaker and control is less complete. When a firm hires a worker, it purchases labor services during certain periods of time. Because labor effort is difficult to observe, the firm does not always get the good for which it has paid. The existing legal system cannot enforce this kind of contract at all well. It would be absurd to propose that the firm go to court and sue for compensation whenever the employee leaves work early. Firms therefore find ways to execute transactions with their workers that are cheaper than writing explicit legal contracts that list all contingencies and then litigating every dispute. This is what the transactions cost theory of the

firm is all about.³ It emphasizes that firms are institutions that provide alternative systems for establishing property rights and enforcing contracts. These institutions make possible investments and gains from trade that would otherwise be impossible to exploit.

At the bottom of the column are examples such as fish in the sea or the sterile insects that are released in agricultural settings to control pests. Fish and insects are objects. They are rival goods. The insects can neutralize fertile pests in my valley or yours, but not both. They unambiguously belong in the left-hand column. Control over these goods, however, is especially weak. If one farmer paid for and released sterile insects, the benefits would spill over onto the farms of his neighbors. Much of the economic analysis of policy is framed in terms of these spillovers—these instances of incomplete property rights. Control can be weak, so spillovers can be present, both for rival and nonrival goods.

The right column lists examples of pieces of pure information with various different degrees of control. An encrypted satellite television broadcast, the kind used to distribute movie channels to cable television systems across the country, is a pure nonrival good with very strong property rights. Musical recordings, microprocessor designs, and computer code are examples of goods for which control is less than perfect but which nevertheless are supplied by commercial firms able to sell their goods in the market at a significant markup over marginal cost. The kind of knowledge possessed by the Wal-Mart corporation about managing retail stores is only partly controlled—other firms copy what it does. That knowledge nevertheless represents an asset in which a firm can invest and on which it can earn a sizable return.

Next come goods over which control is even weaker—these include goods such as the general principles that are the basis for chemical engineering, the insights behind the notion of a window-based graphical user interface for computer programs, or basic ideas such as the do-loop in computer programming. Finally, at the bottom, are goods, such as results from research in physics, that are nonrival and whose use is virtually impossible to control. Economists call these pure public goods. (The term is somewhat misleading because not all public goods are provided by the government—think of charitable contributions to

3. See, for example, Coase (1988); and Williamson (1975).

support public television. Moreover, not all goods provided by the government are what economists call public goods—think of the sterile insects.)

One of the most important insights in economics is that if people have strong control over ordinary objects (those in the upper left corner of the table where the private goods are) and if there are many potential buyers and sellers, decentralized exchange between self-interested traders leads to efficient outcomes. This is the lesson of *laissez-faire*, or the invisible hand. If control over objects is weak, outcomes may be inefficient—as in the proverbial tragedy of the commons. Everyone will be a free rider. These results are the basis for the strong, almost unthinking reaction among some economists that moving up the columns of the table and increasing the degree of control will always enhance efficiency. If others cannot be excluded from enjoying the benefits of some service, the government may collect taxes and pay for the service, as it does for the release of sterile insects, but this kind of collective action is used only as a last resort. Stronger property rights, this line of thinking suggests, would always be preferable.

This intuition is correct for rival goods but simply does not apply to nonrival goods, where strong property rights are inherently associated with monopoly power. If there are strong property rights, there cannot be many sellers. If firms that produce nonrival goods are to avoid large losses, these goods must sell for a price that is higher than marginal cost. Marginal cost on bit strings is zero, but the initial fixed costs of producing them can be very large.

To see why extremely strong property rights might be a problem, imagine that Bell Labs had been given a nonexpiring, ironclad patent on the discovery of the transistor. Or even worse, imagine that such a patent had gone to an organization such as IBM or General Motors. Think of how different the digital electronics and consumer electronics industries would be if every inventor who improved on the design of the transistor and every person who applied the transistor in a new setting had to negotiate with one of these large, bureaucratic organizations for permission to proceed. Not only would the prices have been higher, but the rate of discovery of all the inventions that reduced the cost of transistors would have been lower. These kinds of discoveries, which were made by many different individuals in many different firms,

have in just a few decades caused a millionfold reduction in the cost of producing a transistor.

A standard response to concern about strong patent rights is the claim that if GM had owned the patent on the transistor, it would have had an incentive to do everything right—to make all the right inventions and to agree to efficient contracts with outsiders. The relevant retort is that GM has had an incentive to find innovative ways to design and build high-quality automobiles and has not always succeeded in doing so. In the car business consumers are protected by the presence of a diverse set of competing manufacturers. But with an effective patent, all of the eggs would necessarily be placed in a single corporate basket.⁴

Or consider the computer software industry, an area of economic activity where producers are exquisitely aware of the need for some degree of intellectual property rights and monopoly power. Many thoughtful participants have also recognized that property rights can be too strong. Monopoly power can impose serious distortions and negotiation costs. Imagine, they say, if someone had been able to obtain a long-lived patent on the do-loop or the blinking cursor.

If people were pathologically honest and compulsively followed instructions, the economic problem of producing nonrival goods would be easy to solve. (This definitely is political science fiction.) In this kind of world, undertaking collective action would pose no problem. Everyone would diligently search out new opportunities for discoveries as they went about their other activities and would report all they learned to a central, coordinating agency. The government would direct a subset of these people to do the R&D necessary to take advantage of the most promising opportunities. The government could request that everyone else contribute a share of their income to the researchers who produced the desired nonrival goods—the software, the movies, the music, the books, the microprocessor designs, the innovative ways to organize a retail chain, the technological and scientific discoveries. These producers of nonrival goods could then give away all of the underlying discoveries at marginal cost, zero.

A world populated by real people instead of these science fiction

4. See Merges and Nelson (1992) for an extended evaluation of these kinds of costs from strong property rights.

automatons faces two distinct problems in providing nonrival goods: how to share costs and how to select the most promising opportunities for investment. Real people will choose to be free riders if they can. They will not share the fixed costs of goods that are freely disseminated if they do not have to. In addition, assembling all the information necessary to decide which of the extremely large number of possible nonrival goods to produce is difficult. The kind of calculation showing that there are many wonderful things to discover also implies that there are an almost infinite number of ways to waste effort on interesting but socially useless nonrival goods. Think about software. About $10^{1,000,000}$ different bit strings can fit on a 360K floppy disk. For comparison, a year has about 10^7 seconds, and about 10^{18} seconds have passed since the big bang. Out of $10^{1,000,000}$ possibilities only a very small fraction need to be useful for there to be many useful software programs still to be discovered. But so many other possibilities also are available that all human ingenuity for the rest of time could be devoted to producing useless computer code.

The government's powers of coercion make it uniquely capable of solving the cost-sharing problem. Unfortunately, these powers also make the government uniquely capable of wasting large amounts of resources on socially useless purposes. (Recall the experience in the savings and loan industry.) Markets, conversely, can solve the sharing problem only by introducing monopoly distortions, but they are better than governments at selecting the opportunities to pursue and avoiding wasteful spending. Because people operating in the market are motivated by the potential for profit, they seek out only those nonrival goods that have real value. The parallel or simultaneous search by large numbers of market participants can efficiently evaluate many possibilities. Bankruptcy constraints quickly cut off the flow of resources to projects that turn out to be unpromising.

Under the existing institutional arrangements for producing nonrival goods, one or the other of these extreme mechanisms is typically selected as being most appropriate for a given type of good. In the public good portion (the bottom) of the nonrival column, the government pays for basic research and gives away the results. This arrangement is chosen partly because dissemination of these goods is so important. (Think, for example, of the polio vaccine.) In addition, because of the efforts of Vannevar Bush and people like him, the institution of peer

review of competitive research grants is now available. It offers a reasonably good solution to the problem of selecting which projects to fund.

For nonrival goods at the top of the column, there is little prospect of setting up a government body that could make the right decisions about what to provide. No one would take seriously the suggestion that the government should extensively subsidize the production of popular music recordings, movies, or the design of new kinds of microprocessors so that these goods can be sold at marginal cost. Instead, society relies on market mechanisms to make those decisions and accepts the limits on dissemination and the monopoly distortions that the use of the market entails. The monopoly markups on compact disks, movies, and microprocessors cause relatively small welfare losses, and selecting which goods to produce poses an institutional design problem that dwarfs the problem faced in basic research.

The existing arrangement with government provision of basic research and market provision of final goods seems to work reasonably well for nonrival goods at the top and bottom of the column. It is the intermediate zone where the most important opportunities may now be missed. This region includes what Richard Nelson has called generic research. As he argues on the basis of case studies in different industries, this area may offer particularly large returns from investment in research.⁵ It includes goods such as the principles of chemical engineering, the insights behind the design of computer interfaces, and the fundamentals of program design. It is this region that my proposal tries to address through its mixture of government and private sector mechanisms. Without trying to identify in advance what these areas are and what the specific opportunity for collective action is, the proposal seeks to create a mechanism that combines the government's efficiency at solving free-rider problems with the market's effectiveness in selecting practical problems that offer the highest rates of return. Market participants can then make the right decisions about where the returns on investment are highest for the industry.

More is at stake here than just the rate at which knowledge is transferred from basic research to commercial application. These areas play a special role as the intermediaries between the basic research com-

5. Nelson (1983).

munity and the final users of technological knowledge in an economy. Better communication here is important not just for commercial outcomes, but for the vitality of the basic research endeavor. Without some point of contact with the practical opportunities and challenges of the world, basic science risks drifting into irrelevancy. The recent trend toward closer contacts between individual firms and universities avoids the problem, but firms pay for research only if they get proprietary control over the results. These arrangements therefore tend to undermine the traditions of open dissemination of ideas that have made our universities so successful. The proposal outlined here could provide a mechanism for connecting industry with universities, without jeopardizing the traditional role of the university.

Economic Magnitudes

Economists have uncovered a great deal of evidence suggesting the economic importance of nonrival goods. In his very useful survey of the econometric work on spillovers from R&D, Zvi Griliches describes one of the first attempts to compute a social rate of return on investments in R&D.⁶ T. W. Schultz computed the total resources saved by technological change in agriculture, compared the savings to total expenditure on R&D, and found a high ratio of benefit to cost.⁷ In his refinement of this calculation, Griliches himself found that the social rate of return on public investment in research on hybrid corn had a rate of return of about 40 percent, a number illustrative of the magnitude of returns on investment in R&D that has been found in many subsequent investigations.⁸ A sample of discoveries has been used to make this kind of calculation both in agriculture and in manufacturing.⁹ It has also been made in agriculture, in manufacturing, and at the national level by means of regression analysis using data on total factor productivity.

Three conclusions emerge from this large body of work. The first is that the social rate of return to investment in the broad class of nonrival goods is quite high, on the order of 30–50 percent. This level of return

6. Griliches (1992).

7. Schultz (1953).

8. Griliches (1958, p. 425).

9. Mansfield and others (1977).

confirms the claim made above that these are in some sense the most important kinds of investments that can be made. Second, the research demonstrates that the social rates of return are significantly higher than the private rates of return. This gap can arise because firms that produce new nonrival goods have only weak control or property rights over them. Alternatively, it can arise because property rights are strong; monopoly pricing then induces its own wedge between private and social values. The third conclusion is that economists cannot estimate the *ex post* rate of return in any one industry or area of economic activity with anything like the precision required if econometric estimates alone were to be used to make decisions about where to direct research dollars. This literature offers no support for the idea that academics or bureaucrats will be able to read the numbers and pick winners.

The calculation by Griliches suggests that the difference between private and social benefits from research is important for more than the microeconomic details. The macroeconomic effects of this difference can be quite large. Using the calculated social rates of return to investments in R&D, he can explain the majority of the total factor productivity growth at the national level as the result of measured spending on R&D. And this kind of calculation must lead to an underestimate of the importance of nonrival goods because it cannot capture the kind of innovation that led, for example, to discount retailing in the United States. Wal-Mart no doubt does not show up as a big player in the R&D statistics but has nevertheless helped transform an extremely important sector of the economy, significantly lowering costs in the retail sector. Griliches' calculation is also consistent with the recent cross-country regression estimates by Lichtenberg and by Coe and Helpman suggesting that social returns to R&D, measured at the national and international level, are still very high.¹⁰

Principles of Political Action

Having made the case that there are important opportunities for collective action to encourage the production of nonrival goods, especially in areas of practical importance, I now evaluate the potential costs of

10. Lichtenberg (1992); Coe and Helpman (1993).

trying to undertake collective action. In doing so several general principles suggest themselves. Other observers would no doubt add to the list and might change the emphasis, but the generalizations listed below should not be particularly controversial.

Reaction

Every policymaker operates in an environment characterized by competition among many different independent policymakers. A government of divided powers, such as ours, has a number of policymakers, and every government in the world must take account of the actions of other governments.

In this setting any change in policy can induce a reaction from other policymakers. A good working hypothesis is that policymakers operate in a strategic environment characterized by tit-for-tat and in which the details of what others are doing are sometimes hard to discern. This suggests a sequence of tests in evaluating any policy initiative:

- *Self-interest.* Would a policy be worth adopting if no other policymaker changed policy in response?
- *Reflection.* Would a policy be worth adopting if other policymakers responded by adopting the same policy?
- *Robust reflection.* Would a policy be worth adopting if other policymakers responded by adopting similar but more pernicious policies?

These tests reflect increasingly sophisticated views of strategic behavior. The self-interest test applies when there are no other players or in a one-time strategic interaction. The reflection test applies in cases of repeated interaction—what economists call a repeated game. The robust reflection test applies in cases of repeated strategic interaction if the actions or motivations of other players are difficult to observe—that is, in a repeated game with asymmetric information. In both of the reflection tests, the implicit model of the policy equilibrium is based on trigger strategies in which all parties defect as soon as one does.

One example that bears directly on technology policy and that suggests the importance of the robust reflection test can be cited.¹¹ In the

11. This account is based on Crease (1991) and Office of Technology Assessment (1991).

early 1980s George Keyworth, then the science advisor to President Reagan, invented the concept of a ‘‘Presidential Initiative’’ and simply put a \$140 million item in the Department of Energy budget to support funding for a National Center for Advanced Materials (NCAM), bypassing all of the usual mechanisms of peer review.

Suppose for the purposes of argument that this project represents a good investment in science and technology and thus passes the self-interest test. Suppose also that it passes the reflection test in a policy game between Congress and the executive branch. If both sides begin to use the special initiative process to fast-track high priority science and technology projects that are truly in the national interest, the net effect would be positive.

What Keyworth did not anticipate was that Congress would behave differently from the way he did because members of Congress face incentives that are different from his. They used the freedom from peer review to fund projects of dubious scientific value. At the same time that Congress rejected Keyworth’s attempt to bypass the traditional procedures with his presidential initiative (which was eventually funded after undergoing peer review), it approved two congressional initiatives that also bypassed all peer or agency review and that had no apparent justification in terms of national interests. For example, one initiative gave Columbia University \$24 million to renovate its chemistry building. (In a play on Keyworth’s words, this was referred to as the National Center for Chemical Research.)

These actions marked the end of the traditional consensus that basic research funding had to pass peer review and would not be eligible for congressional earmarking. Universities began to hire their own lobbying firms and compete actively for earmarked funding. Senators and representatives now compete to provide resources for their constituents. Since 1982 earmarked research funds have grown from \$9 million a year to \$470 million in 1991 and \$707 million in 1992.¹² For comparison, the annual budget for the entire National Science Foundation is about \$2 billion.

Almost everyone concedes that much of the congressionally earmarked funding represents pure pork-barrel spending. The academic community, the executive branch, and the defenders of traditional sci-

12. Savage (1992, p. 8, table 1).

ence in Congress have tried to put the genie back in the bottle but to no avail. For example, when the Bush administration tried to rescind funding for specific examples of pork-barrel science, Congress threatened an extended battle of tit-for-tat by canceling funding for thirty-one specific research grants for the National Science Foundation and the National Institutes of Health. The Clinton administration initially said the right things but has subsequently backed down and gone along with the intentions of Congress.

One can always argue that Congress would eventually have developed a high level of earmarked pork-barrel funding on its own, but the specific sequence of events and the testimony of participants suggests that Keyworth's initiative played a crucial role in the shift from the old equilibrium to the new one. If so, it did not pass the robust reflection test.

Delegation

The dissatisfaction with congressional earmarking as a mechanism for allocating funds to universities reflects a general principle. Successful decisionmaking on matters of science and technology policy requires that responsibility for specific spending decisions be delegated to a body that is not under the direct control of members of Congress. For example, delegation is the key element in the success of the peer review system. It is the mechanism whereby members of Congress commit to each other that they will refrain from pursuing special advantage for their constituents as long as everyone else refrains as well. The lack of delegation is at the heart of the failure of many science and technology projects that must, because of their large dollar cost, be directly funded by Congress. The summary by Cohen and Noll of the results from six case studies of large commercialization projects (the supersonic transport, satellite technology, the space shuttle, the Clinch River breeder reactor, the synfuels project, and the photovoltaics commercialization program) is illustrative. "The overriding lesson from the case studies is that the goal of economic efficiency—to cure market failures in privately sponsored commercial innovation—is so severely constrained by political forces that an effective, coherent national commercial R&D program has never been put in place," they wrote.¹³

13. Cohen and Noll (1991, p. 378).

The problem with direct political control of large discretionary spending projects is one of incentives, not ethics. Members of Congress are rewarded in large part for providing services and benefits to constituents. This creates strong incentives to select projects for reasons that do not have much to do with economic efficiency or even institutional missions. For example, the only possible explanation for the fact that the National Aeronautics and Space Administration (NASA) has been authorized to build the Christopher Columbus Center of Marine Research and Exploration in Maryland, a project the agency did not request, is that the senator who chairs the panel that writes the NASA appropriation is from Maryland. Even if the ultimate goal of this or any other senator is to do the very best job possible of promoting national science and technology objectives, the first priority is to build a strong local power base to ensure reelection.

From an institutional point of view, the problem is further compounded, because what Congress can delegate, it can also take back. A consensus that everyone should refrain from seeking narrow advantage in some area of government activity can easily break down if the opportunity presents itself and the temptation becomes too large. Some proponents of direct government funding for specific kinds of commercial innovation point to the former Defense Advanced Research Projects Agency (DARPA) as an agency comparable to the National Science Foundation, able to make independent decisions free from congressional interference. This may have been true in the past, when its activities were clothed in secrecy and were not widely understood. But lawmakers from Michigan inserted \$25 million into the fiscal 1993 defense budget to fund purchases by what is now called ARPA of flat panel display screens. (To emphasize the increased importance that this agency is to place on technologies that have both civilian and military applications, the new administration has taken "defense" out of the name.) It will come as no surprise that the legislation was written so that the company best positioned to fill the request happened to be located in Michigan.¹⁴ Officials at ARPA reportedly disapproved, but they know where their funding comes from. They wrote a request for proposals that favored the Michigan firm and are now negotiating a final purchase contract.

14. Carey (1993).

Inertia and Competition

A third general principle is that large organizations are very difficult to change. They seem to adapt to changing circumstances only when confronted with serious competitive threats. This generalization seems to apply equally well to private and public sector organizations. Large companies such as Ford and Chrysler, which are now two of the low-cost, high-quality automobile manufacturers in the United States, began the major reorganizations that transformed their operations only after being faced with the serious prospect of bankruptcy. (Some economists point to the government's intervention to save Chrysler as a success. Perhaps, however, the government should have demonstrated its willingness to let a big-three automaker fail. If it had, Ford and especially GM might have begun to change much sooner.) Similarly, while the rest of the Soviet economy fell further and further behind Western levels of output and technology, the Soviet arms industry—propelled by the intense pressures generated by military competition—managed to manufacture fighter aircraft that were roughly on a par with those made in the United States.

This suggests a role for competition that is quite different from the one economists teach to students. Competition in this sense has nothing to do with price-taking and tangency conditions. Instead, it affects the power that the leaders of a large hierarchical organization have to overcome the incentive and monitoring problems that tend to plague these institutions under normal circumstances.

Reaction, delegation, and organizational inertia are general considerations that policy analysis in any country of the world should address. The next two issues are somewhat more specific to the current political and institutional context in the United States.

Pay as You Go

In the current budget climate in the United States, no large new spending program can be undertaken unless it includes a funding source. The magnitude of the change in spending priorities that an aggressive technology policy might contemplate makes the importance of this observation clear. The substantial difference between the social and private rates of return to investment in nonrival goods and their relatively small share of total investment suggests that it would be

reasonable to consider an increase in annual spending on R&D of as much as 1 percent of gross domestic product, or roughly \$60 billion a year. This is not an impossible amount to contemplate in a \$6 trillion economy, but it is a very large amount to raise in new taxes in the midst of the current budget climate in Washington.

Divided Government

The American system of government was intentionally designed to limit the ability of any one part to take decisive, unilateral action. Subsequent developments, such as the recent erosion of the seniority system and party discipline in Congress and the expansion of the powers of the judiciary have probably pushed the system even further in this direction. The government is not an actor. It is a game with a very large number of players, many of whom can veto, or at least delay, any proposal. The equilibria that result are quite different from those that emerge, for example, under a parliamentary system.

To see the relevance of divided government for technology policy, consider two examples. First, ARPA (and before it, DARPA) has explicitly encouraged technological development of massively parallel supercomputers. It picked particular firms that it aided during the development of prototype machines. Firms that were not favored have objected to the perceived favoritism and have managed to instigate, no doubt through their local congressional representatives, a General Accounting Office investigation of ARPA that was critical of its supposed favoritism.

Set aside the question of whether ARPA is right that massively parallel computing is an important area of technology. (It almost surely is.) Also set aside the more problematic question of whether ARPA is able to pick the most promising firms in this area. The relevant point is that any agency directly answerable to Congress is increasingly unable to exercise any independent judgment about important technical issues. Soon, the selection of technology projects at ARPA will look like the rest of military procurement.

Military procurement is, of course, a familiar whipping boy. The Air Force, for example, has been trying to buy a large quantity of desktop computers for years now under its new "expedited" bidding process. The winner has been announced twice, only to be overruled when losing

bidders protested to the General Services Administration board of contract appeals. As James Q. Wilson has emphasized, the inflexible, rule-driven, excessively bureaucratic nature of procurement is an inevitable outcome of a process in which a losing party has access to multiple bodies—members of Congress, other agencies, or the courts—to question the integrity and professionalism of the person who made the decision to give the bid to someone else.¹⁵

Evaluating the Self-Organizing Industry Boards

The economic case for creating the industry investment boards has already been made. The opportunity for collective action is a logical consequence of the existence of nonrival goods. (So, for that matter, is the potential for economic growth.) The private sector-government hybrid proposed here would use the tax system to share the cost of producing new nonrival goods, and it would use market forces to solve the selection problem of deciding how the funds could best be invested. Private, for-profit firms would make the decisions about the relative importance of various industry-specific public goods and whether these interests are sufficient to justify any funds at all. In addition, both the industry boards and the organizations, such as research universities, research labs, and training schools, that they might support would be forced to compete for funds. Thus, both private sector incentives and competitive pressures can be brought to bear on the selection process.

If it succeeds, this mechanism could support investments that span the gap between the most general forms of basic research and the product development activities of individual firms. During the past few decades new discoveries in this gap have been funded only if they bear on the health care or military missions of the federal government. Because other practical areas have been neglected and because support for health- and defense-related research is likely to contract in the coming years, it is particularly important to find a new way to select the practical problems that motivate good fundamental research and create economic value. A new source of funds to support work on these problems must also be found.

15. Wilson (1989).

Another, more subtle advantage of this kind of proposal is that it addresses broader issues than those typically considered in the technology policy debate. As Henry Ergas has emphasized, explicit government policies affecting procurement, subsidies for firms, diffusion, or the educational system take place within a broader economic and institutional context that crucially determines their effectiveness.¹⁶ Implementation of this proposal can empower firms in various industries to change some of the basic features of this larger context. They can change, for example, the patterns of interaction between university researchers and those in industry. They can change the system of training at the postgraduate or vocational level. They can create new institutions for setting standards. In so doing, they can enhance the effectiveness of the policies that governments now take (too often with little success) to encourage the commercial application of new technology.

Some of the details of the proposal could be debated but are of secondary importance. For example, the primary effects of selecting a specific tax will come from investing the revenue in an area with large disparities between private and social returns. The distortions associated with different kinds of taxes will be second-order small. The decisive issue in selecting the tax will come not from the conventional analysis of elasticities and deadweight losses, but from the costs of collection and enforcement. Industry participants would have the right incentives to minimize these costs and should therefore be given wide latitude to propose their own enforcement mechanisms.

The political case for this particular proposal is somewhat more complicated. This system was explicitly designed to survive the robust reflection test. If every country decided to compete internationally by creating private sector initiatives that support industry-specific versions of Bell Labs, or open versions of SEMATECH, or new schools of biotechnical engineering, everyone would benefit from the discoveries that result. The federal government would certainly want to insist that other countries offer the same treatment to U.S. firms that they offer to domestic firms. If such a system were adopted in another country, the U.S. government would also insist that the spending must be transparent and that it not be used to offer continuing subsidies to domestic firms in an industry. If differential treatment or direct subsidies were possible,

16. Ergas (1987).

there is a real risk that even if the United States did not abuse this kind of arrangement, other countries could and would.

This proposal is also designed to ensure an adequate degree of delegation. The only effective way to do this is to make sure that the decisionmakers can operate without having to go through the congressional appropriations process each year. (This is why the Federal Reserve Board is independent in a way that no other quasi-governmental entity is.) Absent this freedom, the kind of interference that is beginning to occur at ARPA is sure to arise here as well. Finally, the provisions specifying free entry of new industry boards are designed to ensure that the inertia that typically saps the effectiveness of any complacent organization will not affect prospects for an entire industry—or for the nation as a whole.

In more parochial terms, the proposal is obviously designed to be self-financing and is tailored to keep any new financing arranged under this proposal isolated from the ongoing and protracted debates about federal budget priorities and deficit policy. As the example of the FDA fees suggests, it is not entirely unrealistic to believe that firms in some industries would be willing to back the required taxes if they could control how the proceeds are used. Finally, this kind of system, unlike any government agency, would be capable of decisive action because it would be free from interference from the legislative and executive branches of government.

One of the most serious (and certainly the most frequent) complaint about this proposal is that it may not work for all industries, perhaps not even for very many of them. Compared with a multibillion dollar program that puts control of innovation into the hands of some technology bureaucrats, this proposal is indeed less aggressive. But if one believes that the risks from careless intervention by the government are potentially very large, this built-in conservatism is an advantage, not a weakness. The imperative in policy design, as in medicine, should be to do no harm. In its current form, this proposal will be exploited only in industries whose participants perceive benefits that are large enough to justify the costs to them of the tax (which may in fact be small) and the costs of setting up and administering the system (which may be large). Where it is implemented, society will very likely derive important gains. Where it is not, the case for other, stronger measures must

be viewed as open in principle, but with a very strong burden of proof on those who call for more explicit government intervention. Surely, the right way to proceed in formulating policy is to try the less risky, less intrusive measures first and save the measures favored by advocates of aggressive government intervention for later.

If this criticism is right, this mechanism will be implemented in few places. If so, there is less to be gained by creating this process, but little risk in trying. And the criticism may well not be correct. For many areas the opportunities seem to be large, and the mechanics of collecting the tax straightforward. For example, the telephone and cable TV industries could agree to a common, 1 percent revenue surcharge that would be used to support research and training on new digital communications and the interface between computing and imaging.¹⁷ In effect, these industries could recreate the source of funds that once supported the rich interaction between practical problem-solving and fundamental research that took place at Bell Labs. Given the increasing likelihood that the “Baby Bells” will end up directly competing with each other (for example, through links with cable firms that operate in the service area of another phone company), the existing arrangements that support BellCore may erode. In any case, BellCore, the part of the original Bell Labs now controlled by the telephone operating companies, probably could benefit from being exposed to a more competitive research environment.

One could imagine an industry initiative by semiconductor manufacturers, with a tax of, say, 20 cents per million transistors on all domestic chip sales. If a firm in the semiconductor manufacturing industry believes that the SEMATECH consortium deserves support, it could use

17. After this paper was written, I learned of a research organization called CableLabs in Boulder, Colorado, that collects a voluntary charge of 2 cents per subscriber per month from the operators of cable television systems. Contributing firms cover 85 percent of the subscribers in the United States and about 70 percent of subscribers in Canada. CableLabs employs a small number of scientists and contracts out much of its research to universities, public and private research laboratories, and some equipment suppliers to the industry. It is currently working on problems such as digital compression and digital transmission of cable signals.

The fact that an organization very close to the one described here could come into existence even without the support of legislation that solves free-rider problems suggests the existence of a much larger unmet demand for the kind of collective industry-specific investment activity than skeptics have realized.

its funds to ensure support once ARPA withdraws its funding, as it is now scheduled to do. SEMATECH could compete with universities for funding from an industry-controlled research board, provided it operated according to the open disclosure and equal access rules required under the new system. If the research board did not believe that SEMATECH was a good investment, it could use its funds to support basic research at universities or the national labs. Other boards could support graduate training fellowships, worker training, or whatever other need they perceived to be most pressing.

One could also imagine initiatives in machine tools or in automobile assembly and design. More prosaic economic areas such as construction might also be covered, perhaps in subsegments such as single-family home construction, an area that seems to have been conspicuously lacking in technological progress.¹⁸ A new initiative for electrical power utilities might compete with EPRI in areas such as electricity storage. Biotech firms could use their funds to create a school of biotechnical engineering that could do for them what chemical engineering at MIT did for the petroleum and chemical industries in the United States.¹⁹ Software firms could tax shrink-wrapped software to help pay for basic research in computer science or to establish better curriculum standards, testing, and teaching at the junior college and undergraduate level. Software firms might also benefit from the creation of a software engineering discipline separate from the pure research activities of existing computer science programs. These schools could support the systematization of private sector knowledge about principles of software engineering and could train skilled professionals for software production rather than for university research, just as chemical engineering serves these functions for the petroleum and chemical industries. This kind of change in the institutional infrastructure could prove to be far more important for an industry than any particular government program of subsidies or attempts to pick winners.

In any industry complicated details of administration and tax collec-

18. See Nelson (1983) for a discussion of previous attempts to transfer the successes of the extension service in agriculture to the homebuilding industry. At least part of the problem in previous initiatives has been the attempt to implement the program from the top down, rather than meeting needs that were perceived by industry participants.

19. Rosenberg and Nelson (1993).

tion would have to be worked out. For example, if a tax of 20 cents per million transistors were levied on semiconductor chips, some decision would have to be made concerning the level at which tax obligations would be calculated and monitored. Typically, firms try to avoid responsibility for taxes, but under this proposal, control of how the funds are spent comes along with responsibility for collecting the tax. A tax per transistor could be levied when a semiconductor manufacturer such as Intel sells one of its chips. Intel would be responsible for reporting its total sales of transistors and would be able to decide which industry research board would get its taxes. When Toshiba exports memory chips to the United States, it could be responsible for reporting sales and could allocate its tax obligations among different boards. Alternatively, a firm such as Dell Computers that buys semiconductor chips from Toshiba would be responsible for reporting its purchases of transistors not already covered by a tax payment and could decide how these tax obligations would be allocated. One could even leave the choice of who pays the tax and controls the revenue up to the firms involved. Toshiba could sell some chips on which the tax has already been paid if it wanted to control some of the tax revenue. It could also sell some chips on which taxes have not been paid if Dell or another purchaser wanted to pay the tax and control the proceeds. All that would be required is that someone pay the tax before the goods move into the hands of the final purchaser.

A little thought would be needed to resolve the practical details, such as implementing a system for keeping track of the chips on which tax payments have already been made and those on which they have not. This problem is the kind that a government agency might find very difficult to solve or might solve by imposing large costs on the private firms that have to comply with its rules. But private firms routinely solve all kinds of difficult logistical, contractual, and monitoring problems. Dairy cooperatives make sure that fresh milk is always on the shelf in the grocery store. Railroads keep track of freight cars that are shuttled among different trains operated by different companies. Employers make sure that workers actually do their jobs in the absence of effective legal enforcement of employment contracts. Policy analysts should not underestimate the ingenuity of private firms in solving monitoring, enforcement, and tax collection problems in their industry if

they perceive it to be in their interest to do so. And if firms do not perceive this program to be in their interest, it will not even be attempted.

Perhaps the biggest risk inherent in this proposal is that existing firms in an industry might use it to protect themselves from new competition. For this to take place, some degree of collusion between existing firms and the government would almost certainly be necessary. The requirements for openness and the oversight powers of the secretary of commerce would make it very difficult for existing firms to limit competition without at least tacit government approval. Unfortunately, cases in which the government would collude with the threatened firms in an industry are not hard to imagine. For example, the United Steelworkers have proposed a surcharge of \$5 a ton on all imported and domestic steel to cover unfunded pension and health care obligations at large steel firms. This is a clear attempt to tax the new, innovative, nonunion minimill steel producers and subsidize the existing firms and their workers. The United Auto Workers are also considering this kind of arrangement for the automobile industry. Because the government, through its Pension Benefit Guarantee Corporation, is faced with large potential losses on the pension obligations of the largest steel and auto firms, it might be willing to go along with this kind of scheme.

Nothing prevents Congress from passing this kind of surcharge as a separate measure, but it could not be imposed surreptitiously under the structure of the industry investment boards. The enabling legislation would specifically prohibit any kind of spending activities by boards that would shift costs from or transfer resources among existing firms. The ultimate protection, however, comes from the freedom that firms in an industry have to create alternative boards and to control how funds are spent. Even if the established steel producers, because of their size, could impose an industry-wide tax that minimill operators do not want, the established producers have no way to coerce the minimill operators to fund an Industry Pension Board. The minimill operators could merely establish a separate board devoted to research on new technologies for minimills and refuse to contribute to any board dominated by the old, integrated producers.

The freedom to create new boards and to choose among competing boards is so important that any proposal that did not include these

provisions would have an entirely different character. Without these protections, the political risks would loom very large compared with the potential economic benefits.

Alternative Technology Policy Proposals

The criteria listed above can be used to evaluate other technology policy proposals.

Increased Funding for Basic Research at Universities

Funding for basic university research has until recently received broad support from economists and politicians, partly because the economic advantages of free dissemination of basic scientific discoveries are so obvious. In addition, the delegation problem has largely been solved. Peer review delegates resources to the scientific community, which decides what issues to pursue within broad guidelines established by the funding agencies. (But as noted above, this delegation function is increasingly threatened by direct congressional earmarks that bypass peer review.)

More and more policymakers, however, are realizing that the existing arrangement solves only one part of the broader selection problem of deciding which areas deserve additional research support. Spending is concentrated on pure scientific research and on practical problems in the areas of health and defense, but too few resources are devoted to areas of basic research and training that are motivated by the commercial opportunities faced by private firms. Because policymakers are beginning to emphasize the commercial relevance of research and because budgetary and geopolitical changes may reduce mission-oriented basic research in health and defense, the amount of support universities receive for basic research may soon decline substantially. From a practical point of view, the relevant question is not how much government support for basic science at universities can be increased, but whether the current level can be preserved.

To understand how a system of industry investment boards could protect the existing level of support for pure research at universities

and at the same time address the reasonable concerns of policymakers for a commercial payoff from some kinds of research, it is useful to look at the history of universities in the United States. As Nathan Rosenberg and Richard Nelson demonstrate, the university system in the United States has always paid a great deal of attention to practical problems and has contributed enormously to their resolution.²⁰ But the nature of those practical problems has changed dramatically over the years.

Before World War II universities primarily addressed practical problems faced by commercial interests. The land grant universities were devoted to agriculture and “the mechanic arts.” Farming, railroad transportation, electrical generation and transmission, and chemical processing all required their own specific kinds of technical research and training. Europeans sneered at the vocational orientation of higher education in the United States during the nineteenth century and the first part of the twentieth century, but Americans derived important national economic benefits from a responsive university system. To illustrate that responsiveness, Rosenberg and Nelson describe the emergence of programs of electrical engineering. In 1882—the same year that Edison opened the first electrical station in New York—MIT introduced its first electrical engineering courses. Cornell followed in 1883. By the 1890s schools of electrical engineering were the primary suppliers of skilled professionals for the electrical industry, having supplanted unsuccessful attempts by firms to train engineers in house.

This experience was not unique. Universities trained people for work in many areas of commercial importance and developed bodies of knowledge that could be used there. They did not do this, one can be sure, entirely out of patriotism or dedication to national economic success. Universities were attentive to private sector opportunities because the private sector paid the bills.

During and immediately after World War II, the federal government became by far the largest patron of research and advanced training at universities. This shift in funding accompanied a shift toward solving practical problems in health and defense and pursuing more abstract problems. The Department of Defense and departments with related

20. Rosenberg and Nelson (1993).

missions (Energy and NASA) provide the majority of all research support in the engineering disciplines. The total expenditure at the National Institutes of Health is five or six times larger than the budget at the National Science Foundation.

There is a continuing debate about whether this postwar shift in emphasis has been beneficial for the business sector. Many observers say that the commercial spin-offs from military research have decreased in recent years. The typical interpretation of this finding is that civilian and military technologies are diverging for exogenous technological reasons. An alternative explanation is that the initial surge in funding from the government in the immediate postwar years stimulated a system that for historical reasons was still attentive to commercial applications and opportunities. As the system evolved in the 1960s and 1970s, however, its connections to the civilian business sector atrophied. The increasing divergence may therefore reflect the delayed effects of incentives and funding rather than exogenous technological developments.

However this debate is resolved, the end of the Cold War clearly means that defense-related support for research will be substantially reduced in the next decade. Moreover, the enthusiastic support for technological advance in medicine and health may increasingly come under attack as the nation tries to come to terms with the rapidly escalating cost of medical care. Some policy analysts are already suggesting that because new health technologies are not being priced and allocated correctly, slowing the rate of technological advance would be the best way to control health care expenditures.

Stagnation, or even real cuts in government funding for university research, is thus a distinct possibility. Moreover, demands will grow for more direct commercial payoffs from research. This pressure is reflected, for example, in the controversial planning process that Director Bernadette Healy tried to impose on biological research funded by the National Institutes of Health in 1992. Responding to congressional pressure, she tried to adjust the decision process and priorities of the traditional peer-reviewed, basic research program to give greater emphasis to commercial objectives. In the current institutional environment, this pressure could undermine the strengths of the existing basic research system without generating the hoped-for commercial benefits.

The National Institutes of Health, the National Science Foundation, and the Department of Defense are unlikely to be the best institutions for assessing commercial opportunities.

A more productive response to politicians and voters who ask for research and training that have closer economic payoffs would be to agree to a division of labor. Basic science agencies such as the National Institutes of Health and the National Science Foundation could continue to fund the most adventurous and forward-looking research at their existing levels, and an independent source of funds could be created for the commercially relevant research that should be under the control of people in the private sector who are knowledgeable about the opportunities. These funds could fill in part of the gap that would open if mission-oriented funding in defense and health is cut back. Such a dual system could both restore the strengths of the pre-World War II connections between universities and the private sector and preserve the advantages of the more abstract basic research system that developed after the war. It might also provide more total funding than is currently available. The system of industry investment boards would establish this more balanced arrangement.

It is important to recognize (as Rosenberg and Nelson do) that an increased emphasis on practical problems is completely consistent with a division of labor in which universities concentrate on basic research, where free dissemination of knowledge is most important, and firms concentrate on R&D activities over which property rights should be strong. It would be very unwise for university researchers to perform proprietary research for private firms, yet many collaborations between business firms and universities or teaching hospitals are now taking precisely that direction. Universities in search of additional funding are increasingly seeking out arrangements under which they give up some of the traditions of open science and in effect become research subcontractors employed by private firms. Because the industry investment boards can solve, or at least mitigate, the free-rider problem, they can support universities and help set the research agenda without endangering the free exchange of ideas.

Closer interaction between firms confronted with practical problems and researchers pursuing fundamental questions may lead not just to bigger economic benefits but also to better basic science. For example, solid state physics was enormously stimulated by an attempt at Bell

Labs to solve a reliability problem with vacuum tube amplifiers. The labs had scientists on staff who knew some of the basic properties of semiconductors from solid state physics. They used this knowledge as a basis for their experiments leading up to discovery of the transistor. This discovery fed back into the basic research and training activities of solid state physicists and completely transformed the field. High temperature superconductors and opto-electronic devices are just two of the many underexploited opportunities that pose as many challenges for basic scientists as they do for practical problem solvers. These areas are at least as promising for the pursuit of basic knowledge as is the search in high energy physics for “the God particle,” using ever more expensive particle accelerators.

In summary, issuing the perennial call for a massive increase in federal support for existing basic research programs at universities is a totally unrealistic approach to a technology strategy. It is politically unrealistic and would not by itself generate much in the way of economic benefits. It might not even produce better basic science. The real challenge will be to keep government support for basic science from falling. At the same time, universities will feel growing pressure to contribute more directly to economic performance. Unless these pressures are channeled in a constructive way, they could undermine much of the strength of the basic research system, without achieving the desired practical benefits.

R&D Tax Credit

On efficiency grounds the optimal R&D tax credit would be so generous in its definition of R&D activity that no corporation would pay any income tax. Because of the widely acknowledged distortions that arise from the double taxation of capital income (once as corporate income, then as individual income), the efficiency gains from abolishing the corporate income tax would be large.

The United States has a corporate income tax for political reasons, not on grounds of economic efficiency. The potential for substantial increases in the generosity of the R&D tax credit is therefore limited by the lack of substitute funding sources and sensitivity to the political risks of giving “tax preferences to corporations instead of people.” If politicians continue to insist on raising revenue from the corporate

income tax, an argument can be made, in principle, for taxing R&D capital less heavily than physical capital because R&D has a higher social rate of return. In practice, the crucial issue is whether the tax authorities are able to distinguish R&D spending from other kinds of spending. Corporations will surely get better at redefining what they call R&D in response to bigger tax incentives for doing so. Over time, the revenue cost of each additional dollar of new R&D generated through this mechanism will grow. As a result, serious practical limits will be placed on the size of the subsidy that can be provided in this way as long as substantial revenue is collected through the corporate income tax.

Compared with other, more specific technology policies, the R&D tax credit is relatively safe politically, which no doubt explains why it has attracted broader political support than direct subsidies to firms. In effect, the tax credit specifies an aggregate level of subsidies for R&D, and then it solves the delegation problem by letting individual firms select their own R&D projects.

Whatever the decision on the constrained, second-best level of the corporate tax rate and the R&D tax credit, it should be clear that R&D spending by private firms (like government-funded pure basic scientific research) is a complement to the kind of industry-specific public goods that the industry investment boards would provide. Taken together, these three mechanisms (private R&D in firms, government support for basic research, and industry support for industry-specific public goods) would cover most of the spectrum of new ideas illustrated in the non-rival column in table 1.

Infrastructure

Increased funding for infrastructure as a technology policy has at least two serious strikes against it. First, no economic case can be made for infrastructure as a good that requires collective action. Very little infrastructure is a nonrival good. At best infrastructure is what is called a club good in public finance, and these goods can be efficiently provided by decentralized action in markets. Except for the bargaining problem over rights-of-way that is readily solved by the powers of eminent domain, no collective action is needed to provide infrastructure. (The state could use its powers of eminent domain to assist in land

acquisition where necessary but still rely on private sector decision processes in all other areas.) If anything, governments should be moving away from government-subsidized infrastructure and toward greater *reliance on market-like mechanisms such as congestion charges on roads and competition among providers of basic telephone service*. Localities or even private firms should be allowed to select and fund infrastructure projects.

The second problem is that federal funding for infrastructure is rife with the kind of waste inherent in a system that lacks any degree of delegation in project selection and funding. The government continues to provide support for “mass transit” that defies all economic logic. (My favorite example is the subsidy for the buses in Vail, Colorado, that take skiers through town and between ski lifts.)

The dollars at stake in decisions on popular infrastructure projects are truly frightening. A plausible estimate for the cost of roadbed construction for magnetic levitation trains is \$60 million a mile. Just putting in the track for a train that runs from Boston to Chicago could cost \$60 billion, or about thirty years worth of funding for the National Science Foundation.

Dual-Use Technology

Many advocates of a more aggressive technology policy have pointed to the apparent successes at DARPA as a model for a more activist role for the government. This approach should set off all kinds of warning bells about serious political risks. The most important problems pertain to funding, delegation, divided government, selection, inertia, and the robust reflection test.

The funding problem is self-explanatory. Budget constraints mean that the federal government is highly unlikely to make available enough funds to undertake a technology policy initiative that could make much difference on a national scale. The delegation problem has already been noted in the discussion of the contract for research on flat panel display screens. ARPA will be under increasing pressure to conform to congressional demands, especially if its budget grows. ARPA projects would then offer the best opportunity for every member of Congress to provide an identifiable local project. ARPA projects would soon look like infrastructure, earmarked pork-barrel science projects, and military pro-

curement. Asymptotically, every technology project would have part of its spending located in every congressional district, and the selection process for projects would become increasingly rule-bound and bureaucratic.

In its proposal on technology policy, the National Academy of Sciences Panel on the Government Role in Civilian Technology proposed that an independent civilian technology corporation be created with a one-time grant from the government of \$5 billion.²¹ This proposal reflects the panel's appreciation of the importance of the delegation and divided government problems, but it cannot be regarded as a true solution. A private corporation would in principle be free to make independent decisions and would not be subject to vetoes and second-guessing by multiple actors in the government. But the proposed \$5 billion initial grant is far too small to make a permanent contribution to a national technology policy. (This relatively low figure was presumably selected in the hope that Congress would fund it. Even at this low level, funding now seems extremely unlikely.) The interest income on \$5 billion would be about \$250 million a year. Compare this with the \$5 billion or more that IBM and GM each spend on R&D annually. Surely, the proponents of the Civilian Technology Corporation are assuming that if the corporation succeeds, it could go back for more funds. But that means the corporation would have to be highly responsive to the wishes of members of Congress from the start.

The comparison with IBM and GM also raises a caution about the selection problem and institutional inertia. Some proponents of the ARPA, or government planning, approach argue that industry leaders are not competent to make the right decisions about technology in the way a few key people at DARPA are alleged to have done. The countervailing argument is that putting all of the public's technology resources into a single hierarchical, bureaucratic structure leaves no protection if that organization stops producing valuable results. None of the existing proposals put any competitive pressure on ARPA or an independent technology corporation. If the entire auto and computer industries had depended on GM and IBM for all of their innovation, cars and computers would now be much less useful than they are. That

21. Panel on the Government Role in Civilian Technology (1992, p. 94).

is true even though the research staffs in both corporations are highly talented and even though some discoveries of real value have emerged from both institutions (for example, catalytic converters from GM and high temperature superconductors at IBM.) There is no substitute for competitive pressure on any such organization.

Even if all of the other objections could be met, the technology agency approach is probably not the kind of policy that passes the reflection or robust reflection tests. It is all too easy to imagine that an ARPA or a well-funded civilian technology program could be used to subsidize something like the European Airbus program, which Americans now find so objectionable. Mechanisms for direct government subsidies to firms may not be something that the United States wants to encourage in other countries.

Research Joint Ventures

Interest in the United States in research joint ventures seems to have been motivated primarily by the success of the VLSI (very large scale integration) joint venture among semiconductor firms in Japan, an example that is now understood to have been unusually successful and not representative of the typical outcome. Research joint ventures suffer from the obvious economic problem that they cannot solve the free-rider problem and achieve free dissemination of the results at the same time. What has been attempted in the United States, for example at SEMATECH, is a mixture of some degree of insider advantage that is promised to participants in the joint venture together with federal matching funding to sweeten the pot. One half of SEMATECH funding was provided by DARPA, so if this model were to be adopted more widely, all of the concerns about delegation and divided government that apply to DARPA would extend to the government-assisted joint venture.

But if government funds are not used, in any instance where several firms in an industry find it in their interest to work together on a research project, they presumably will be motivated to do so by the availability of important special advantages that accrue only to members of the joint venture. Such cases should raise serious concern that collusion in research will lead to product market collusion. A research joint venture

could, for example, become the vehicle for preventing new entry into an industry or for reducing total industry expenditures on research.²² Compared with the proposal outlined above, in which all joint effort has to be directed at activities that are freely available to any current or future participant in the industry, the research joint venture seems to hold out much greater risk of reduced total research and product market competition than do industry investment boards.

Managed Trade: Import Restrictions

Managed trade comes in two flavors, import restrictions and market access requirements. Import restrictions have the appeal that they are, in effect, self-financing. Import quotas, for example, can generate additional revenue for protected firms without imposing an explicit tax. Import restrictions suffer from almost every other conceivable problem. Some firms will support this option out of naked self-interest, but virtually no economist is willing to try to make a serious intellectual case for these measures.

Managed Trade: Market Access Requirements

Proposals that the U.S. government demand adequate access to foreign markets are more problematic. The purely economic case here is stronger than many economists who support free trade would like to admit. Market access is a necessary condition for effective protection of intellectual property rights. Suppose, for example, that a foreign country enforces a ten-year quarantine on all imported foreign software to check for software viruses. (Sounds plausible, right?) Domestically produced versions of word-processing software, spreadsheet programs, and other kinds of applications that are close copies of the versions available on world markets would no doubt be written and sold in this country. The effect for U.S. software firms would be as if the foreign firms simply sold bootleg versions of their programs. Formal copyright protection is worth nothing if a firm is deprived of the right to sell its goods.

It is not clear that market access restrictions would be in the self-interest of the foreign country. It depends on how costly the copying

22. For a discussion of these issues, see Katz and Ordover (1990).

process is and on what effects the protection has on domestic incentives. The experiences in Brazil, with its failed computer industry, and in Japan, with its (allegedly) protected personal computer industry, do not speak well for the long-run success of this strategy. If a protected domestic market were truly the key to export success, NEC and the Brazilians should have taken over the market for personal computers in the United States, but they have not. For internal political reasons, many countries may nevertheless restrict market access. The United States must therefore decide how it should respond to these restrictions.

Some advocate unilateral punitive measures, but this approach fails the robust reflection test. If market access requirements were given the same status as intellectual property rights and were monitored and enforced through a multilateral body, they would be beneficial. But a unilateral decision by the United States to adopt punitive measures as it sees fit could ultimately have very serious negative affects on the institutions that now support free trade. This would effectively condone the principle that countries can take unilateral action when they are unhappy with trade outcomes. Many other countries would soon start instituting punitive measures that are supposedly intended to punish market restrictions elsewhere but that are, in fact, pure income transfers to powerful domestic groups.

Moving ahead with unilateral punishments would be like announcing an intent to drive through red lights whenever no cars are coming on the cross street. We may believe that no harm will come from our actions if we use our new powers judiciously, and we may even be willing to let others do what we do if they promise to be as responsible as we are. The ultimate outcome is nevertheless likely to be one that we regret.

A useful comparison would be to contemplate the consequences of repealing the interstate commerce clause in the U.S. Constitution and letting individual states take punitive action whenever another state restricts market access. (Many state governments in the United States currently do try to give the same preference to local firms that the Japanese government apparently gives in procurement.)

Economists would almost universally agree that giving each state the power to interfere with interstate commerce would not be the way to deal with market access problems within the United States. The same argument presumably suggests that the United States should work to

strengthen the General Agreement on Tariffs and Trade and the available multilateral institutions in the hope of moving trade among countries closer to the substantial, but not quite perfect, freedom that now prevails among the states of the United States.

Nevertheless, attacks on restricted market access will continue to be a very attractive political strategy for the federal government. Such attacks can be used to aid a small number of firms with high visibility. They do not require budget expenditures, they typically raise little domestic political opposition, and a confrontation with bad guys from another country always plays well in politics. (The war over the Falkland Islands may indeed have been like two bald men fighting over a comb, but it did wonders for the popularity of the Thatcher government.) Of all the policies described here, saber rattling and punitive measures designed to open foreign markets are the most likely candidates for a technology strategy in coming years.

Conclusions

In one of the last things he wrote, the late George Stigler concluded an essay on monopoly with these words: “The merits of laissez-faire rest less upon its famous theoretical foundations than upon its advantages over the actual performance of rival forms of economic organization.”²³ Any discussion of technology policy should take these words as both a warning and a challenge. The warning is that even after admitting all of the deficiencies of economic markets, one must acknowledge what experience has so clearly demonstrated—that most of the familiar political alternatives are far less efficient mechanisms for allocating resources than the market is. The challenge for economists is to understand why markets perform well and then to build upon their strengths. The problem with the classical description of laissez-faire is its suggestion that the best of all possible arrangements for economic affairs has already been discovered and that it requires no collective action. The lesson from economic growth is that collective action is very important and that everything, including institutions, can always be improved.

23. Stigler (1993, p. 402).

The reality of economic life is that the pure individualistic market exchange invoked in the usual defense of laissez-faire has been supplanted by many institutions that allow collective action and improve on pure individualistic market exchange. Perhaps the most important such institution is the limited liability corporation, an invention that would not have been viable without the emergence of supporting regulatory and legal institutions. Other examples of institutional innovation include private universities, copyrights and patents, corporate research laboratories, and peer-reviewed competitive grants for research.

Each of these institutions represents an attempt to take advantage of the opportunities for mutually beneficial coordinated action that are presented by the world in which we live. Each is consistent with the operation of markets and supports success in the market as the final test of economic activity. Each builds on or emulates at least some of the strengths of the market: the push to do better that comes from competing against rivals, the pull that comes from opportunities for individual gain, the diversity that comes from having many different individuals and organizations working in parallel to achieve a given end, and the discipline that comes from clearly enforced criteria for success and failure. From this broader perspective, the “theoretical foundations” to which Stigler attached relatively little importance—the notions of price taking and tangency conditions—are only one small part of the picture.

This paper has tried to place the discussion of technology policy in this larger context. It has tried to shift the discussion away from narrow questions about whether the market or the government is better. It has avoided conjectures about which sectors should be given government support or about what are the most important “critical technologies.” Instead, it has suggested that the debate focus on the underlying processes that lead to effective institutional arrangements.

To a large extent, market competition has become a process for selecting ever better corporate institutions that can channel the energies of large numbers of people toward the production of ordinary private goods. This paper describes a parallel process for selecting ever better institutions that can channel the energies of large numbers of people toward the production of the new discoveries that drive economic growth.

The process outlined above combines government-like aspects (man-

datory taxes that solve free-rider problems) with market-like mechanisms (free entry, competition among different institutions, and decisions that are ultimately grounded in opportunities for profit). It is designed to fill the gap between private and public support for R&D. The essence of the proposal is to empower the firms in different industries, giving them the tools needed to solve the collective action problems inherent in providing industry-specific public goods. The proposal protects product market competition among firms and encourages competition among the organizations that would provide industry-specific public goods such as research or training. The argument is premised on the idea that long-run growth depends on our ability to discover innovative ways to arrange the limited stocks of objects. It concludes that the prospects for growth could be enhanced by searching for equally innovative ways to arrange our institutions.

Comments and Discussion

Comment by Zvi Griliches: This is an exciting paper. It is nice to see somebody young tackling big policy issues. The paper builds on an analysis of the past, but it is basically about the future. It is suggesting new mechanisms and new institutions to solve pressing economic problems. It takes as its historical example the “invention” of land grant colleges and the development of Bell Labs. It sees unlimited opportunities for investment in both basic and applied research and is looking for mechanisms that could provide the financing that would launch the next expeditions into the wide unknown.

The two basic assumptions of the paper are, first, that the research opportunities are out there and, second, that without new financing institutions, we may not get there. I believe that Romer is right on both counts but that the evidence for the first is not as overwhelming as he assumes it to be and that the particular institutional innovation may not work as well as advertised—but nothing ventured, nothing gained.

I will focus on the second point first. I see two difficulties with Romer’s proposal. The first deals with the incidence of benefits from and the costs of technical change in an industry. Implicitly, a high elasticity of demand is assumed for the products of the various industries. Because the benefits from this research will be public, they are likely to be competed away and not redound to the benefit of the original investors in these boards. Moreover, if demand were inelastic, as in agriculture, such technical change could reduce the rents to the scarce resources in these industries and might be counterproductive from the private point of view. Thus, industries might not vote for such a levy if they see through it.

Second, if there are several boards and I am a small producer, I may choose to contribute my share to a peculiar board, specializing, for example, in supporting economic research at the University of Chicago, on the assumption that the big guys will give to the important research purposes anyway and that my contribution to those boards is unlikely to affect the industry's fate by much. In other words, allowing for alternative boards and for freedom of choice among them may still leave free-rider problems, even within this framework. Nevertheless, the proposal may be worth trying. People may not be as selfish as economists say they should be.

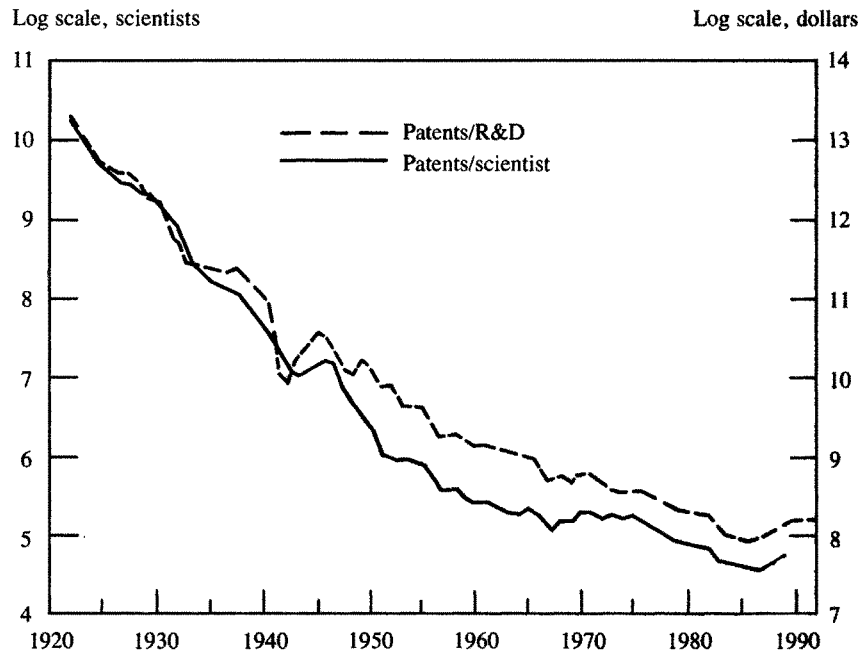
The more difficult notion is the one of the "endless frontier," the absence of diminishing returns to research. Because I have been worrying about this lately, I will focus the rest of my remarks on what we do not know about it.

One can ask two related questions about this. Are our recent "slow-growth" problems caused by a shortfall of research and development? And will encouraging more R&D be helpful here? I don't think that the sharp recession of the mid-1970s and the subsequent slow growth were the result either of the decline in the rate of aggregate R&D investment that occurred in the late 1960s and early 1970s or of a fall in the "potency" of these expenditures. The timing and magnitudes are all wrong.¹ It is probably a good thing to pursue more R&D in any case, for reasons of long-term growth, but not as a solution to our current problems. (Of course, Romer is not saying that his proposal will solve these problems, but it is the current economic situation that gives his proposal its resonance.) We are not currently constrained by our production possibilities frontier. Much existing knowledge is not being used yet. Much more diffusion of computers and learning about them is still in store. And the economy could be made much more efficient by eliminating a variety of barriers to its functioning. Nevertheless, R&D is one of the relevant margins, and we should be exploring it.

But before we encourage more R&D by creating new institutions, we have to face the crude evidence of diminishing returns to it. Figure 1 plots the ratio of patents to company-financed R&D for the last seventy years. If patents are taken as an indicator of inventive output, then the news is not all that good. Bronwyn Hall's paper in this volume

1. See Griliches (1988) for an elaboration of this argument.

Figure 1. Domestic Patent Applications per Company-Financed R&D in Industry (1972 dollars) and per Scientist and Engineer, 1921–92.



Source: Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970*, pt. 2 (Department of Commerce, 1975), chap. W; Patent and Trademark Office, *Technology Assessment and Forecasts* (Department of Commerce, March 1977), app. A; National Science Board, *Science and Engineering Indicators*, 1991, NSB 91-1 (Washington); and Patent and Trademark Office releases. Number of applications by residence of inventor for 1940–59, unpublished memorandum of P. F. Fredrico, Patent and Trademark Office, January 18, 1961; for 1960, *Journal of the Patent Office Society*, 44 (February 1964), p. 168; for 1961–62, Commissioner of Patents and Trademarks, *Annual Report*, 1966, p. 26; for 1963–91, Patent and Trademark Office releases; extrapolated back, before 1940, by the number of total applications. Data on company R&D and the number of scientists and engineers in industry from the same sources, updated from NSF Reports 92-307, 92-330, and 92-331. Deflated by R&D price index from Griliches, "Comment on Mansfield," in *R&D, Patents, and Productivity*, (University of Chicago Press, 1984) p. 149, and Bronwyn H. Hall and others, "The R&D Master File Documentation," Technical Paper 72 (NBER, December 1988), updated.

Note: Left scale is the log of the number of domestic patent applications per 1,000 R&D scientists and engineers. Right scale is the log of the number of domestic patent applications per \$1 million of company-financed R&D (in 1972 dollars).

shows a significant decline in the market's recent valuation of R&D. Evidence claiming to show exhaustion of inventive opportunity was presented by Baily and Chakrabarti at these same meetings some years ago, and Evenson looks at the international evidence on patenting and comes to similar conclusions.²

I myself do not think these facts need to be interpreted so pessimistically, but before we urge significant additional investments in R&D,

2. Baily and Chakrabarti (1988); Evenson (1993).

we need to convince ourselves that this would be a good investment. My own optimistic reading of these same data is based on scattered evidence that the economic “meaning” of patents has changed. This is the only reasonable way to interpret the fact that ratios of patents to R&D have been falling consistently, until quite recently, through good times and bad. If we did not worry about it in the 1950s and 1960s, when total factor productivity growth was rapid, why should we worry now? Moreover, even while—according to Hall’s estimates—the market’s valuation of new R&D was falling sharply, firms were expanding their R&D investments at rates not seen since the 1950s! Did companies know something that the market did not, or were they all lemmings? At the moment we face two contradictory facts: domestic patent applications started growing sharply in the late 1980s, indicating some revival of inventive activity, while the growth in companies’ real R&D expenditures slowed to a crawl and may have actually turned negative. But overall, if the numbers are to be believed, we are not investing less in R&D today, relative to the size of the economy, than we did in the peak years of the 1960s. It is a puzzlement.

An argument can be made that precisely because we may have been facing the exhaustion of inventive opportunities, we need more R&D, but R&D of a special kind, the basic kind, the kind that would “re-charge” the pool of knowledge and increase the effectiveness of the rest of it, which is spent on “D,” rather than “R.” We need additional investment in science and basic research to make the run-of-the-mill company’s R&D more productive. In this sense, Romer’s new institutions, specializing in basic and “generic” industrial R&D may be just what the doctor ordered. But what we want is basic research and basic results that will not be appropriated by individual firms, and I am not sure that we will succeed in convincing such firms to tax themselves for the public good.

I do want to dissent from Romer’s view that the fact the molecules can be arranged in an infinity of ways implies an “endless” frontier for R&D exploration. It may not be feasible to discover the work of a new Shakespeare in the random typing of monkeys, even if it is there. More seriously, the notion that there may be no diminishing returns to research in the long run, and the associated notion of a permanent exponential growth of real income per capita, is a dream full of hubris, the notion that man is God-like and not subject to serious constraints

or hard choices. Many years ago, in commenting on the “old” growth theory, Arrow remarked that “eternal exponential technological growth is just as unreasonable as eternal exponential population growth.”³

The fact that the frontier may not be endless need not be taken pessimistically. First, we are still very far from being there. And, second, much is left to do to improve the situation as it is, including the diffusion of already-known technologies and the dismantling of the many manmade barriers to economic efficiency. Technological change is still endogenous, even if it is not endless, and although the outcomes of science and research are largely out of our hands, better economic understanding still has much to contribute. Schmookler, in one of the last things he wrote, complained about the state of this field: “. . . it may leave scientific and technological progress unexplained, which is unsatisfactory; alternatively, it explains scientific and technological progress as self-generated, which is dreadfully wrong. Such a view is wrong both scientifically and morally. It is wrong scientifically because . . . it is simply not true. It is wrong morally . . . because it deprives man generally of any sense of responsibility for the course of social and economic development. For if [technological change is endogenous], then all men must accept some measure of responsibility for what happens next.”⁴ It is admirable that Romer is willing to do just that.

General Discussion: In evaluating the potential of the author’s plan, several participants raised examples of past experience with cooperative research efforts. Pointing out that few firms have formed research joint ventures in the decade since it first became permissible under antitrust laws, Timothy Bresnahan wondered if there really is an unfulfilled demand for more cooperative research. He also noted that existing cooperative institutions in the form of standards committees (such as ANSI) are abandoned by many in information technology industries when these committees attempt to coordinate the direction of technological progress through anticipatory standard setting. Bresnahan considered the rules imposed by standards committees to be quite modest and argued that the author’s seemingly more restrictive institutional arrangements could prove even less popular.

3. Arrow (1969, p. 34).

4. Schmookler (1972, p. 84).

In contrast, Albert Link said that experience with SEMATECH, the cooperative research venture of the semiconductor industry, shows that cooperation can yield important benefits. Despite others' criticisms of that organization, Link said, it has ensured that American companies are competitive in their production of semiconductor manufacturing equipment, such as wafer polishing tools.

Link, however, questioned whether the author's proposal would succeed in increasing basic scientific research. He maintained that existing cooperative arrangements with universities are becoming more commercially oriented and now almost mirror research that is performed at private firms. Link nonetheless praised the proposal's concern with providing a forum for the more efficient evolution of standards, saying that this could lead to a more rapid diffusion of technology throughout a given industry.

Linda Cohen argued that the coercive part of the author's proposal might make it more viable than existing forms of noncoercive cooperative arrangements. She maintained that noncoercive cooperative agreements work well only in regulated and monopolistic industries (and, for unique reasons, in agriculture), and that they tend to break down under competitive conditions. She noted that when the electric industry became more competitive, Southern California Edison, one of the largest and most innovative utilities, dropped out of the Electric Power Research Institute because the utility no longer wanted to share technology. Using SEMATECH as an example, she argued that when noncoercive cooperation involves the public sector, the results of the research are forced to be more public, allowing many firms to opt out of the arrangement and get a free ride. In competitive markets, she concluded, coercion forcing 100 percent of participation may be the only feasible way to bring about sustained cooperative research.

Michael Katz argued that the government role in the author's proposed arrangement would end up being far more intrusive than the author assumes. He said that government would become integral in determining which firms fall within an industry and which do not. He also suggested that the author's proposal to make imported goods subject to the mandatory industry taxes could lead to abuse if other countries adopted this proposal as well. If his plan were effected in a country such as France, Katz said, nationalized French firms might be able to avoid paying their taxes through offsetting government subsidies, plac-

ing American and other foreign firms subject to the tax under an unfair burden.

Several participants discussed the author's presumption that almost limitless potential gains can be had from pushing out the knowledge frontier. Robert Gordon argued that diminishing returns present a serious constraint to the benefits of technical progress. He suggested that such diminishing returns can be observed by looking at the effects of the technological changes of the past century. Such changes have been transforming daily life over this period, but the rate of transformation has been slowing down. Martin Baily, in contrast, argued that the significant externalities connected with additional investments in research and development make a strong case for pushing out the knowledge frontier.

Robert Hall disagreed with the author's contention that providing extremely strong property rights over nonrival goods would lead to inefficiencies and lost opportunities for additional technological progress. Using the computer industry as an example, he noted that IBM has been liberally granted licenses for the use of its key patents. Bresnahan concurred with Hall's assessment and added that for the commercialization of information technology, the most important mechanism for coordination and reuse is the appointment of a monopoly vendor.

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6 Appendix B

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7

Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?

Paul M. Romer, *Graduate School of Business, Stanford University*

Executive Summary

This paper suggests that innovation policy in the United States has erred by subsidizing the private sector demand for scientists and engineers without asking whether the educational system provides the supply response necessary for these subsidies to work. It suggests that the existing institutional arrangements in higher education limit this supply response. To illustrate the path not taken, the paper considers specific programs that could increase the numbers of scientists and engineers available to the private sector.

Preface

My son attends an undergraduate institution that specializes in science and engineering. A degree from this school will cost more than \$100,000 in tuition and 4 years of his time. For parents and students who contemplate an investment of this magnitude, the school provides information about labor market outcomes for its graduates. On its web site, the school provides the median salaries for students who accepted jobs after graduation and the Ph.D. completion rates for students who go on to graduate school. If you search, you can see the entire distribution of outcomes—a listing for each student of the starting salary or graduate school in which they enrolled.

If my son pursues a doctoral degree after he graduates, he will have to make an even larger investment. Net of the various sources of support that are available to graduate students, the direct tuition cost of a doctorate will probably be less than the cost of his undergraduate degree. He will, however, have to invest another 4 to 8 years of foregone earnings, which will be substantially higher once he completes his undergraduate degree.

His college is unusual. Most undergraduate institutions do not provide any useful information about labor market outcomes for degree recipients. Yet as

this example shows, it is perfectly feasible for a school to provide this kind of information. Given the stakes, it is even more surprising that many graduate programs in science and engineering also fail to provide this kind of information to prospective students. The paucity of information is obvious to anyone who is familiar with the graduate school application process, but to demonstrate it more formally, I asked a research assistant to begin the application process for the top 10 graduate departments of mathematics, physics, chemistry, biology, computer science, and electrical engineering in the United States. (The rankings were taken from US News and World Report.) For comparison, I also asked him to begin the application process to the top 10 business and law schools.

In response to his 60 initial requests for information from the science and engineering programs, he received not one response giving information about the distribution of salaries for graduates, either in the initial information packet or in response to a follow-up inquiry from him. In contrast, he received salary information for 7 of the 10 business schools in the application packet, and in response to his second request, he was directed to a web page with salary information by one of the three nonrespondents from the first round. (It is possible that the information could have been found on the web page for the other two business schools, but to maintain consistency in the treatment of the different programs, he did not look for more information if a school did not respond with directions about where to get it.) Four out of the 10 law schools gave salary information in the application packet and three more of them directed him to this information in response to a second request.

I. Introduction

The most important economic policy question facing the advanced countries of the world is how to increase the trend rate of growth of output per capita. In the middle of the 20th century one might have argued that preventing depressions was the more urgent challenge, but at least in the advanced countries of the world, progress in macroeconomic stabilization policy has reduced the threat of a paralyzing economic collapse and even reduced the frequency of mild recessions. In this environment, the lure of better growth policy is compelling. If an economy can increase its trend rate of growth by even a small amount, the cumulative effect on standards of living is too big to ignore.

Many scholars and policymakers are convinced that during the 20th century, rapid technological progress in the United States drove the un-

precedented growth in output and standards of living we enjoyed. In addition, they believe that this rapid rate of technological change was fostered by a publicly supported system of education that provided the essential input into the process of discovery and innovation—a steady flow of people trained in the scientific method and in the state of the art in their area of specialization.

If this interpretation of our recent past is correct, it follows that any proposal for achieving an even higher trend rate of growth in the United States should take full account of the detailed structure of our current system of higher education for natural scientists and engineers. Policymakers must recognize that these institutions exhibit puzzling features such as those described in the preface—an almost total lack of information on future market opportunities for students who enter their programs.

Unfortunately, in the last 20 years, innovation policy in the United States has almost entirely ignored the structure of our institutions of higher education. As a result, government programs that were intended to speed up the rate of technological progress may in fact have had little positive effect. We have undertaken major spending initiatives in the area of innovation policy, our most important area of economic policy, without subjecting their economic assumptions to even a cursory check for logical coherence or factual accuracy.

In what follows, I will point to the fundamental conceptual flaw behind the government programs that have been used in the last 20 years to encourage innovation in the private sector. These programs try to stimulate the demand for scientists and engineers in the private sector. To succeed, they depend on a positive supply response that the educational system seems incapable of providing. I will also describe a class of alternative policy programs that could be used to fill the gap created by an exclusive reliance on demand-side subsidies. These alternative programs return to an early style of government policy, one that works directly to increase the supply of scientific and engineering talent.

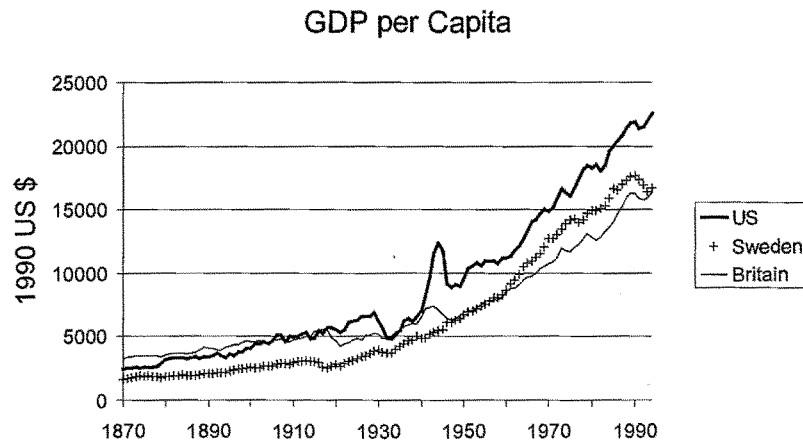
Section II below starts with a quick recapitulation of the reasons why decisions concerning innovation policy are so important for the economic well-being of future generations. Section III shows how a demand-side innovation policy such as a tax credit for research and development or a program of research grants affects the market for scientists and engineers. It shows why even a well-designed and extremely generous program of this kind will fail to induce more

innovation and faster growth if the educational system does increase supply in response to changes in wages. Section IV provides an overview of trends in the supply of scientists and engineers. Sections V and VI look at the market for undergraduates and for Ph.D. recipients respectively. Section VII summarizes and interprets the evidence from these sections.

One of the surprising features of the political debate surrounding demand-subsidy policies is its narrow focus. Few participants in this debate seem to have considered the broad range of alternative programs. Section VIII tries to broaden the debate by suggesting feasible policies that could be considered. More specifically, it outlines a general process that policymakers could adopt for formulating growth policy. This process starts by distinguishing between goals and programs. To be specific, this section outlines four general goals that could guide the formulation of growth policy. The first possible goal that policymakers might adopt would be to target a specific increase in the number of students who receive undergraduate degrees in the natural sciences and engineering. A second would be to encourage more innovation in the graduate training programs that our universities offer to students who are interested in careers in science and engineering. A third would be to preserve the strength of our existing system of Ph.D. education. A fourth would balance amounts that the federal government spends on subsidies for supply and demand of scientists and engineers.

If policymakers in an economy were to adopt goals such as these, the next step would be to design specific programs that are intended to achieve these goals. In broadening the debate, this section also outlines three illustrative programs that policymakers could adopt to achieve these goals. The first is the introduction of training grants to universities that could be used to increase the fraction of undergraduates who receive degrees in natural science and engineering. The second is a system of exams that give objective measures of undergraduate achievement in natural science and engineering. The third is a new type of fellowship, backed by a substantial increase in funding, for students who continue their studies in graduate school.

The advantage of a process that separates goals from programs is that it establishes a natural way to evaluate any specific programs such as these. If the goals are precise and progress toward them can be quantified, then it should be easy to verify if any given program moves the economy closer to the goals. This makes it possible to experiment

**Figure 7.1**

Income per capita from 1870 to 1992 for the U.S., Britain, and Sweden.
Data are from Angus Maddison (1995).

with a variety of programs, to expand the ones that work, and to shut down the ones that do not.

II. The Importance of Technology Policy

A quick look at the data in figure 7.1 suggests that there must be policy choices, intentional or unintentional, that affect the trend rate of growth. Using data assembled by Angus Maddison (1995), this figure plots income per capita from 1870 to 1994 for the United States, Britain, and Sweden. Over the century-and-a-quarter of data presented there, income per capita grew in the United States at the rate of 1.8% per year. In Britain, it grew at 1.3% per year. In the beginning of the sample period, the United States was a technological laggard, so part of its more rapid growth could have come from a process of technological catch-up with Britain, which was at that time the worldwide technology leader. But even at the beginning of this period, it was clear that the United States was also capable of generating independent technological advances—for example, in the area of manufacturing based on the assembly of interchangeable parts. (See Rosenberg 1969 for an account of the reaction that the “American system of manufactures” caused in Britain by the middle of the 19th century.) Moreover, as the United States surged ahead of Britain in the 20th century, it maintained the

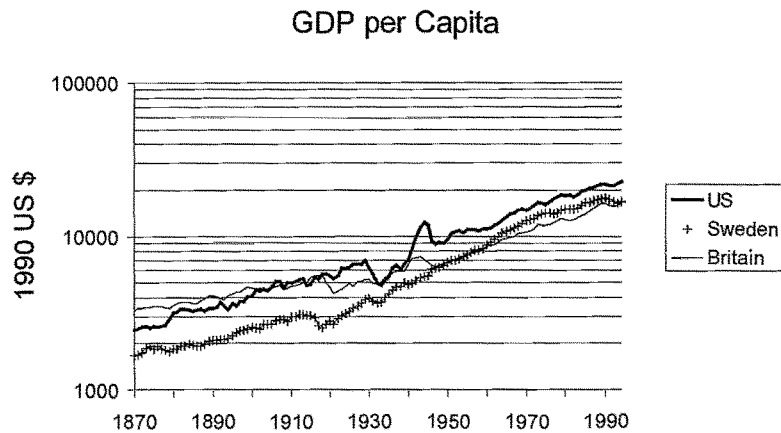


Figure 7.2
 Same data as figure 7.1, on a logarithmic scale.
 Data are from Angus Maddison (1995).

faster rate of growth that was apparent from the beginning. This is most clearly evident in figure 7.2. Because the data are plotted on a logarithmic or ratio scale, straight lines in the figure correspond to constant rates of growth. In the second half of the century, the rate of growth in Britain accelerated moderately. The rate of growth that had been initiated in the U.S. remained essentially unchanged. The policies and institutions in the United States made possible a trend rate of growth of income per person that was significantly faster than the trend that had pushed Britain into the position of worldwide leadership in the 19th century. Given the limited state of our knowledge of the process of technological change, we have no way to estimate what the upper bound on the feasible rate of growth for an economy might be. If economists had tried to make a judgment at the end of the 19th century, they would have been correct to argue that there was no historical precedent that could justify the possibility of an increase in the trend rate of growth of income per capita to 1.8% per year. Yet this increase is what we achieved in the 20th century.

The experience in Sweden suggests that even higher sustained rates of growth of income per capita can sometimes be possible. During the 50 years from 1920 to 1970, income per capita in Sweden grew at the much higher rate of 3% per year. Once again, this faster rate of growth could be due, at least in part, to the process of technological catch-up.

Moreover, growth in Sweden has slowed down considerably since 1970. Nevertheless, the experience in Sweden should at least force us to consider the possibility that if we arranged our institutions optimally, growth in the United States could take place at an even higher rate than that to which we have become accustomed. In the coming century, perhaps it will be possible to increase the rate of growth of income per capita by an additional 0.5% per year, to 2.3% per year.

The implications of a change of this magnitude would be staggering. For example, according to recent CBO estimates that were based on continuation of the historical trend rate of growth, in the year 2050 the three primary government entitlement programs—Social Security, Medicare, and Medicaid—will require an increase in government spending equal to about 9% of projected GDP. If the rate of growth over the next 50 years were to increase by 0.5% per year, GDP in 2050 would be 28 percentage points larger. By itself, faster growth could resolve all of the budget difficulties associated with the aging of the baby boom generation, and still leave ample resources for dealing with any number of other pressing social problems. And of course, the longer a higher growth rate can be sustained, the larger the effect it will have. By the year 2100, the additional 0.5% per year would translate into a GDP that is 1.65 times as large as it would otherwise have been.

Other types of evidence suggest that an increase in the rate of growth of 0.5% per year is not beyond the realm of possibility. In his survey of returns to investment in R&D, Zvi Griliches (1992) reports a wide range of estimates for the social return, with values that cluster in the range of 20% to 60%. Take 25% as a conservative estimate of the social return on additional investment in R&D. If we were to increase spending on R&D by 2% of GDP (and maintain the same rate of return on our investments in R&D—more on this in the next section) the rate of growth of output would increase by the hoped-for 0.5% per year. If the true social return is higher, say 50%, the extra investment in R&D needed to achieve this result would be correspondingly lower, just one additional percent of GDP. These estimates are also consistent with other estimates, which suggest that the level of resources currently devoted to research and development may be far below the efficient level. For example, after they calibrate a formal growth model to the results from micro level studies of the productivity of research and development, Chad Jones and John Williams (1998) calculate that the optimal

quantity of resources to devote to research and development could be four times greater than the current level.

There is another way to look at estimates of this kind, one that is closer to the spirit of the analysis that follows below. GDP in the United States is about \$10 trillion dollars. One percent of this would be \$100 billion per year in additional spending on R&D. If it costs \$200,000 per year to hire and equip the average worker in this sector, this means that we would need to increase the stock of workers employed in R&D by roughly 500,000. The question that policymakers must confront if they are serious about increasing the amount of R&D that is performed is where these additional high-skilled workers will come from.

There is no certainty that growth would necessarily speed up even if we did undertake all the right steps in an effort to do so. There is ambiguity in the historical record, and even if there were not, there is no guarantee that relationships that held in the past will continue to hold in the future. Moreover, even in the best case, we should recognize that there might be substantial lags between the initiation of better policy and the realization of faster output growth. For example, one highly successful example of a government policy that did increase the rate of technological change was the creation of the new academic discipline of computer science in the 1960s. (See Langlois and Mowery 1996 for a discussion of the episode.) Even now, with the passage of 40 years, our sense of the magnitude of the payoff from this investment is still growing.

Notwithstanding all these caveats, a possibility, even a remote possibility, of a change as profound as another permanent 0.5% increase in the trend rate of growth in the world's leading economy ought to excite the imagination. Compared to this, even landing a man on the moon would seem a minor achievement. One would think that this kind of possibility would inspire us to try new things, to make every effort to understand what will work and what will not as we strive for this goal. By this kind of standard, the efforts we have made in the last 2 decades have been remarkably timid and poorly conceived.

III. Demand Subsidies

Unless one is careful and makes use of some simple economic theory, it is easy to fall into an all-too-common trap in discussions about innovation policy. The key point was signaled above in the switch from a discussion of spending on R&D to a discussion of the number of workers

engaged in this activity. To speed up growth, it is not enough to increase *spending* on research and development. Instead, an economy must increase the total *quantity of inputs* that go into the process of research and development. Spending is the product of a quantity and a price. To simplify the discussion, assume for now that people—scientists and engineers—are the key inputs in research and development. Formally, let E stand for spending on research and development and let N represent the number of scientists and engineers working in this area. Let w represent the average wage for these workers. Then trivially, $E = N \times w$. An increase in expenditure E will not necessarily translate into a corresponding increase in N , the number of scientists and engineers engaged in R&D. In principle, it is entirely possible for the entire increase in E to pass through as increases in w .

Continuing with the simplifying assumption that scientists and engineers are the only inputs in the production of research and development, we can illustrate how w is determined using the simple supply and demand framework presented in figure 7.3. The horizontal axis measures the number of scientists and engineers working in the private sector on R&D. The vertical axis measures their wage. The downward-sloping demand curve indicated by the solid line represents the

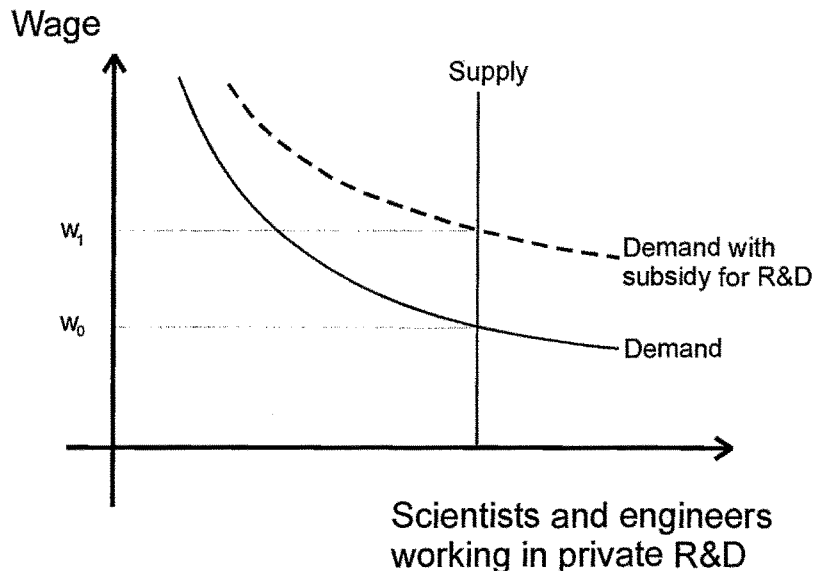


Figure 7.3

Wage w versus number of scientists and engineers working in private R&D

private return captured by a firm that hires some additional scientific workers and undertakes more research and development.

In the figure, the supply of scientists and engineers is represented by a vertical supply curve. The vertical slope of the curve reflects an assumption that the number of young people who become scientists and engineers and go to work in the private sector does not adjust in response to an increase in the wage that they receive for employment in the private sector. Section IV below outlines a much more complicated picture of the supply response of our educational system, but it is useful to start with the simple case of zero supply elasticity. To motivate this assumption, it is enough to keep the story from the preface in mind. The lack of information that is available to students who are making decisions about careers in science and technology suggests that our existing educational institutions may not lead to the kind of equilibration that we take for granted in many other contexts. If students do not have information about what wages will be, it will be much harder for them to adjust their career decisions in response to wage changes.

The downward-sloping dashed line in the figure represents the private demand for research workers when the government provides a subsidy for R&D. This subsidy could take the form of special tax advantages such as those afforded by the research and experimentation tax credit offered in the United States. Alternatively, the subsidy could take the form of cash payments to some firms as part of a cost-sharing agreement in which the government pays part of the cost of a research and development program. This is the kind of subsidy offered by partnership programs such as the Small Business Innovative Research (SBIR) grant program administered by the Small Business Administration or the Advanced Technology Program (ATP) administered by the Department of Commerce. Whether it comes in the form of tax credits or research grants, the effect of government spending is to shift up and to the right the demand for scientists and engineers who can perform the R&D.

From the perspective of a single firm, it seems obvious that a special tax incentive or a research grant will encourage the firm to hire more scientists and engineers and thereby to cause more inputs to be devoted to R&D. Yet one of the most basic insights in economics is that for the economy as a whole, things have to add up. If the total number of scientists and engineers is fixed, it is arithmetically impossible for employment of scientists and engineers to increase at all firms. As illustrated in the figure, if the supply curve of scientists and engineers is fixed, then the increase in demand induced by the subsidy will trans-

late into a proportional increase in wages for scientists and engineers with no increase in the inputs that are devoted to R&D.

It is important to recognize that this argument is separate from the usual concerns about “additionality” that have been raised with respect to R&D demand subsidy programs. People who focus on this problem are worried about how much the demand curve shifts. That is, they are worried that an additional dollar in subsidies does not translate into much additional private spending on R&D. This is a nontrivial issue. The evidence does seem to suggest that more generous tax treatment for R&D leads to higher *reported* levels of spending on R&D at firms. (See for example Bronwyn Hall and John van Reenen 1999.) An additional dollar in tax benefits seems to lead to about one additional dollar in reported R&D expenditure by firms. However, there is much less evidence about the extent to which this increase in reported R&D spending represents a true increase in spending relative to that which would have taken place in the absence of the credit. It is quite possible that some of this spending comes from relabeling of spending that would have taken place anyway. Deciding what qualifies for this credit is apparently a nontrivial problem for the tax authorities. Between 20% and 30% of claimed expenditures by firms are disallowed each year (National Science Board 1998:4-48).

For the SBIR program, Josh Lerner (1999) finds that firms that receive grants from the government experience more rapid sales and employment growth than a comparison group of firms selected to be similar to the recipient firms. This could be an indication that firms that receive grants do devote more inputs to R&D. But it could also reflect unobserved, intrinsic differences between the control group, which was constructed ex post by the researcher, and the recipient group, which was selected on the basis of a detailed application process that was designed to select particularly promising firms. In related work, Scott Wallsten (2000) finds that firms that receive a research grant from the government under the SBIR program seem to substitute these grant funds for other sources of funds, with little or no net increase in spending on R&D.

For both the tax credit and direct grant programs, we can identify a coefficient m which measures the true increase in private spending on R&D associated with each additional subsidy dollar from the government. In each case, there is some uncertainty and debate about how large this coefficient is. But for any positive value of m , the argument outlined above shows that the entire increase in spending may show up as higher wages for the existing stock of workers, with no increase

in the actual quantity of research and development that is performed. As a result, even a well-designed and carefully implemented subsidy could end up having no positive effect on the trend rate of growth for the nation as a whole.

Recent work by Austan Goolsbee (1998) suggests that, at least in the short run, the wage changes implied by a weak supply response are apparent in the data. He compares census data on wages for research workers with time series data that capture the variation in government spending on R&D. Direct government spending is well suited for this kind of analysis because it does not suffer from the concerns about additionality that are present for government subsidies for R&D. Surprisingly, using only these crude data, he finds strong effects on wages. For example, during the defense build-up between 1980 and 1984, federal spending on R&D increased, as a fraction of GDP, by 11%. His estimates suggest that this increased wages for physicists by 6.2% and aeronautical engineers by 5%.

In the face of this argument, defenders of demand-side R&D subsidies can respond in three ways. First, they can argue that people are not the only inputs used in R&D. If other inputs such as computers and specialized types of laboratory equipment are supplied elastically, then government subsidies for R&D could increase the utilization of these other inputs even if the number of scientists and engineers remains constant. If this were truly the intent of the various subsidy programs, it would be much more cost-effective for the government to provide the subsidies directly for these other inputs. Salaries account for the majority of total R&D spending. For example, in university-based research, annual research expenditures on equipment during the last decade have varied between 5% and 7% of total research expenditures (National Science Board 1998). If the goal of the subsidy program were to increase the equipment intensity of research and development and if the ratio of spending on equipment in the private sector is comparable to the figure for universities, a special tax subsidy for the purchase of equipment used in research would be substantially less costly than one that is based on total expenditures including salaries. Similarly, the government could achieve substantial savings, and still increase the use of equipment in R&D, if it restricted the grants provided by the SBIR and ATP programs so that these funds could be used only for additional purchases of equipment.

In the case of the targeted grant programs administered by the ATP or the SBIR, a defender could argue that even if the existing research subsidies do not increase employment of scientists and engineers in the

economy as a whole, they can increase employment at the recipient firms, at the cost of a reduction in employment at other firms. If government agencies were able to identify an allocation across firms and projects that is better than the one the market would implement, the targeted grant programs could still be socially valuable. But even the strongest supporters of the subsidy programs are hesitant to make this kind of claim about the superiority of government allocation processes. Note also that because the research and experimentation tax credit is available to all firms, it cannot be justified on this kind of basis of any hypothesized ability of the government to improve the allocation of research inputs between firms and projects.

If the goal is not to encourage equipment investment in the R&D sector or to give the government a bigger role in deciding how to allocate scarce R&D personnel, some other motivation must lie behind these spending programs. The final response could be for a defender of these programs to dispute the basic assumption behind the supply-and-demand model outlined here and argue that, at least in the long run, the supply of scientists and engineers working in R&D in the private sector does respond to demand-induced changes in wage. But to make this case, one must confront some of the peculiar features of the educational system that actually produces these highly skilled workers and ask if there are more cost-effective ways to increase the supply of these types of workers.

IV. Overview of the Supply of Scientists and Engineers

Figures 7.4 and 7.5 give a broad overview of trends in the supply of scientists and engineers in the United States. Figure 7.4 updates data presented by Chad Jones (1995) on the number of scientists and engineers in the United States who are employed in research and development. These data are scaled by the size of the labor force. They show an increase in R&D employment as a fraction of the labor force from about 0.3% of the labor force in 1950 up to about 0.8% in the late 1960s, with no strong trend thereafter. The underlying data for this figure are collected by the NSF. (Data since 1988 are taken from Table 3-15 from National Science Board 1998.)

Official statistics on formal research and development capture only part of the private sector effort directed at innovation. Also, no consistent data series on employment in R&D is available in years prior to 1950. To give a more comprehensive overview of the proportions of skilled workers in the labor force over a longer time horizon, figure 7.5

Scientists and Engineers in R&D as a Fraction of the Labor Force

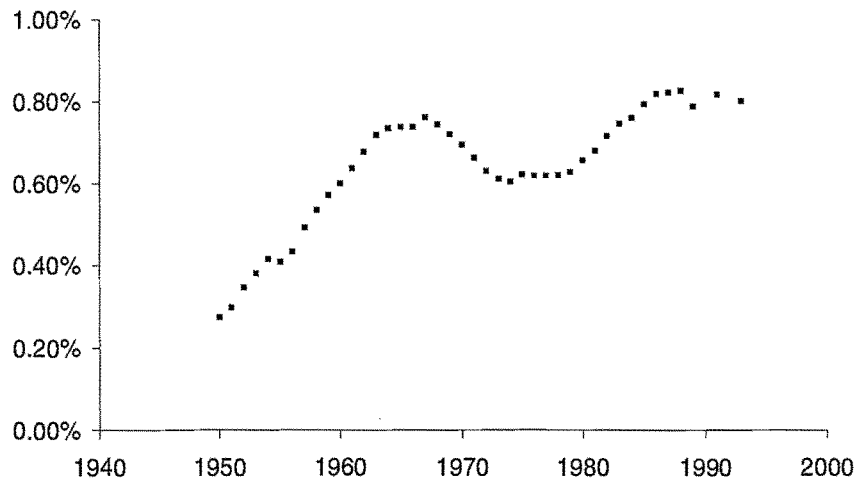


Figure 7.4
Scientists and engineers in R&D as a fraction of the labor force
Data from Chad Jones 1995.

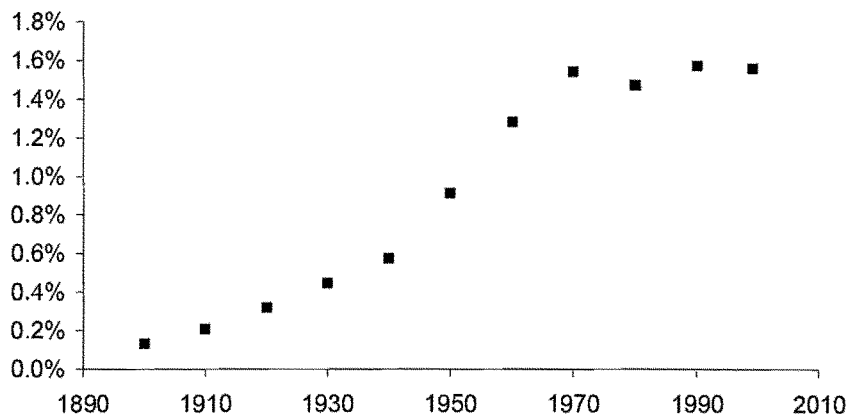


Figure 7.5
Engineers as a fraction of the labor force
Data are from Historical Statistics of the United States, 1975, and Statistical Abstract of the United States, various years.

presents data on the total number of engineers as a fraction of the labor force, using occupational data collected by the Bureau of the Census. This series shows a similar pattern. Engineers increase, as a fraction of all workers, from the turn of the century up until 1970, and remain roughly constant thereafter.

Taken together, these figures offer little reassurance that the aggregate supply of scientists and engineers responds efficiently to market demand. Of course, it is logically possible that the growth in the demand for scientists and engineers experienced a sharp fall starting in the late 1960s. However, other labor market evidence based on relative wages such as that presented by Katz and Murphy (1992) suggests that a process of skill-biased technological change that raised wages for skilled relative to unskilled workers continued at about the same pace in the 1970s and 1980s as in the 1960s. Other work (see for example, Autor, Katz, and Krueger 1998) suggests that, if anything, the rate of skill-biased technological change actually increased in the period from 1970 to 1995 relative to the period from 1940 to 1970. Taken together, these data on quantities plus the independent evidence on the demand for skill suggest that one look more carefully at other possible factors that could influence the supply of scientists and engineers.

Figure 7.6 gives a schematic outline of the process that actually determines the supply of scientists and engineers. The two key stages in the production process are undergraduate education and graduate education. (For simplicity, graduate programs that lead to a terminal master's degree are grouped in this figure with those that provide Ph.D. level training.) The first major branch in the process distinguishes undergraduates who receive degrees in the natural sciences or engineering (NSE degrees) from those who receive all other types of degrees. Section V below looks at the possible nonmarket forces that could constrain this decision. After a student receives an undergraduate NSE degree, she can either go to work in the private sector or continue on to receive graduate training. Section VI looks at recent developments in the market for people with an advanced degree in the natural sciences or engineering.

V. The Supply of Undergraduate Degrees in Science and Engineering

The market for education suffers from pervasive problems of incomplete information. Students contemplating a choice between different institutions typically have very little information about the

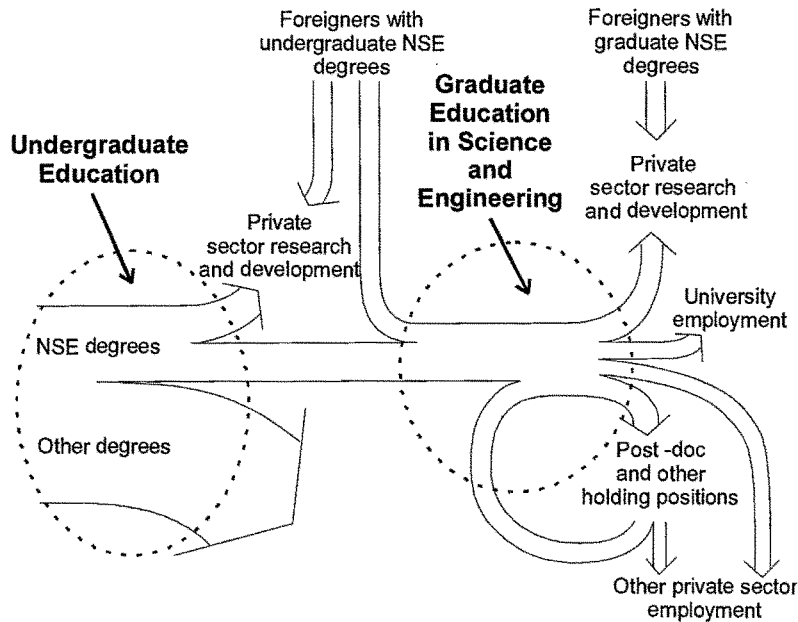


Figure 7.6
Schematic outline of the process determining the supply of scientists and engineers.

value-added they can expect to receive from one institution versus another. Employers selecting among graduates from different institutions also have very little objective basis for judging the absolute achievement levels of students from different schools, or even about students from the same school who have followed different courses of study. The competitive strategy that seems to have emerged in this market is one where undergraduate institutions have developed extensive systems for screening students by ability level. They enroll the most able students that they can attract. The schools compete for these students in large part by publicizing the degree of selectivity. Students, in turn, compete for admission to the most selective institutions because a degree from a more selective institution offers a stronger signal about the student's ability. Using data from the different campuses of the University of California, Robert Frank and Philip Cook (1995) suggest that competition along these lines has been getting more intense. For example, over time, SAT scores for students attending Berkeley, the UC campus that is perceived to be the most selective, have been increasing relative to SAT scores at other campuses.

In this kind of competitive environment, the traditional liberal arts university may face little pressure to respond to changing market demands for different types of skills. For example, imagine that government subsidies increased the market wage for scientists with several years of training beyond the undergraduate degree. Imagine that students are somehow informed about this change in the wage and respond by increasingly enrolling in undergraduate science courses that will prepare them for further study in engineering and science. A liberal arts university that has a fixed investment in faculty who teach in areas outside of the sciences and that faces internal political pressures to maintain the relative sizes of different departments may respond to this pressure by making it more difficult for students to complete a degree in science. Faculty in the departments that teach the basic science courses will be happy to "keep professional standards high" and thereby keep teaching loads down. Faculty in other departments will be happy to make study in their departments more attractive, for example by inflating the average grade given in their courses.

There is clear evidence that this kind of response currently operates on campuses in the United States. First, the number of students who begin their undergraduate careers with the intent of receiving a degree in science and engineering is substantially higher than the number who actually receive such a degree. For example, for white students, 12% of entering students intend to major in natural sciences and 9% plan to major in engineering. Only 8% of graduating students actually receive a degree in natural sciences and only 5% receive a degree in engineering (National Science Board 1998). For minority students, the attrition rate is even higher.

One additional indication of the pressure to shift students out of science and engineering degrees comes from the difference in the distributions of grades offered in courses required for degrees in these areas as opposed to grades in other courses of study. Measuring this difference is not straightforward because even within a department such as mathematics, and even within a specific subject area such as linear algebra, there are courses with easier grade distributions that are intended for people who will not continue toward a degree in science, and courses with a lower distribution of grades for people who will.

For example, students who place out of the basic calculus course on the basis of an advanced placement exam are more likely to take more difficult math courses than students who do not. This tends to lower the average grade they receive in the second-level math courses that they take. If one does not correct for this fact, one finds that math

grades for the students who place out of calculus are not, on average, any higher than math grades for students who do not place out of calculus. However, if one holds constant the specific second-level math courses that students take and compares grades for students with different backgrounds who take the same course, it is clear that students who have placed out of calculus do receive higher math grades than other students taking the same class (Rick Morgan and Len Ramist 1998).

To do this kind of analysis, the College Board, which administers the advanced placement exam, collected data from a representative sample of 21 selective universities. Using these data, one can do a direct comparison of grade distributions across different fields of study. Take, for example, the sample of second-level math courses that students who place out of calculus attend. These tend to be biased toward the classes that students majoring in mathematics or the natural sciences will take. One can then compare the distribution of grades in these courses with the distribution of grades in second-level English courses taken by students who receive advanced placement credit in English composition; or with the distribution of grades in second-level history courses taken by students who receive advanced placement credit in American history. As table 7.1 shows, in the selected math courses, 54% of all students received a grade of A or B. For the English courses, the fraction with an A or a B is 85%. For the history courses, the fraction is 80%. For social science courses such as political science or economics, the fraction of students who receive a grade of either A or B is about 75%.

As figure 7.6 shows, immigration is an alternative source of supply for the labor market in the United States. If the domestic supply of scientists and engineers is constrained to a significant extent by our existing system of undergraduate education, one should see evidence that the response in terms of undergraduate NSE degrees differs from that of immigrants. Recently, much of the discussion of migration has focused on political pressure from technology-intensive firms for increases in the number of H1B visas that permit private firms to hire skilled workers from abroad to fill entry-level jobs in areas such as computer programming. This debate has obscured the extremely important role that immigration has long played in supplying scientists and engineers with the highest levels of skill. Moreover, immigration is clearly responsive to demand conditions. Fields such as computer science and engineering, where indicators suggest that market demand is high relative to the available supply, are the ones that have experienced

Table 7.1
Fractions of students receiving an A or a B in different subjects

Subject Area	Fraction of Students Receiving a Grade of A or B
English	85
History	80
Economics and Political Science	75
Mathematics	54

the largest inflows from abroad. For example, in 1993, 40% of the people in the United States who had a Ph.D. degree in engineering were foreign-born. In computer science, 39% of the Ph.D. holders were foreign-born. In the social sciences, where demand for new Ph.D. recipients is generally much lower (economics being a notable exception), only 13% of the Ph.D. holders were foreign-born (National Science Board 1998). These immigration flows stand in sharp contrast to the trends in undergraduate education. From the mid-1980s until 1995, the number of undergraduate degrees in engineering and in mathematics and computer sciences fell substantially. For example, in the 1980s and 1990s, as the personal computer and internet revolutions were unfolding, the number of undergraduate degrees in computer science showed no strong trend, increasing at first in the mid 1980s, then falling in the 1990s and ending at about the level at which it started in the early 1980s.

Engineering degrees follow a very similar pattern (National Science Board 1998: Table 2-20). Between 1981 and 1995 there is no change in the number of undergraduates who receive degrees in engineering. The number does increase in the late 1980s but then returns to the previous level. For future reference, note that the number of master's degrees in engineering behaves quite differently. From 1981 to 1995 the total number of master's degrees in engineering increased steadily so that the number in 1995 was about 1.7 times the number in 1981 (National Science Board 1998: Table 2-27).

Another sign that the domestic enrollment of students who are able to continue in science and engineering is a critical bottleneck comes from an examination of downstream developments in Ph.D. education. From the mid-1970s to the mid-1980s, the number of Ph.D. degrees awarded in the United States each year in natural sciences and engineering remained roughly constant at about 12,500. (Here, as elsewhere, natural sciences and engineering exclude behavioral and social

sciences.) Then, starting in 1986, this number began a steady increase up to 19,000 per year in 1995.

We can use this expansion in the size of Ph.D. programs to gauge the elasticity of the foreign supply response and compare it to the domestic supply response. In 1986, U.S. citizens accounted for about 8,000 of Ph.D. degree recipients, and noncitizens accounted for the other 4,500. In 1995, the number of degrees for U.S. citizens had increased by about 20% to around 10,000 and the number of degrees awarded to noncitizens had more than doubled to 9,000 (National Science Board 1998: Table 2-35).

A similar, though less extreme picture emerges from an examination of master's degrees, particularly in the high-demand areas of computer science and engineering. As market opportunities for holders of the master's degree increased and universities added to the number of slots that they made available in master's degree programs, foreign students responded more strongly than U.S. citizens, just as they did when new positions in Ph.D. programs opened up. In 1975, foreign students received 22% of the master's degrees in engineering and 11% of the master's degrees in math and computer science. By 1995, foreign students accounted for 39% of the master's degrees in engineering and 35% of the master's degrees in math and computer science (National Science Board 1998). In both instances, increased downstream demand for undergraduates with NSE degrees does not seem to have induced a sufficient supply response. The system equilibrated by importing more foreigners.

VI. The Supply of Ph.D. Degrees in Science and Engineering

The sharp increase in the 1990s in the number of Ph.D.s granted has been accompanied by generally declining job prospects for degree recipients. In the most recent period, it is possible that part of the reason why undergraduate students did not pursue degrees in the natural sciences is that they were vaguely aware of the worsening job prospects that Ph.D. recipients faced. Note, however, that developments in the academic market for Ph.D.s cannot explain the absence of an increase in undergraduate degrees in engineering or in specialized areas such as computer science where job prospects for Ph.D. recipients have remained strong. Also, the weak market for new Ph.D.s would only have been a factor fairly recently, primarily since 1990 when the increased

supply of Ph.D. recipients began to show up on the market. Nevertheless, going forward, the weak academic market for some types of Ph.D.s will certainly be a complicating factor in any attempt at increasing the number of undergraduate degrees that are awarded in natural science and engineering. To increase the number of undergraduates who receive an undergraduate degree in the natural sciences and engineering, they must be convinced that this kind of degree can lead to better career outcomes than the dead-end postdoctoral positions that have become increasingly common in some fields.

Independent of its role in influencing undergraduate degrees in the United States, understanding the behavior of the market for Ph.D.s is critical to the formulation of policy concerning the supply of scientists and engineers. The thrust of the possible programs outlined below is to substantially increase this supply. Yet many people in the academic community are convinced that the most pressing science policy issue in the United States is the Ph.D. glut. They have advocated measures that would reduce the supply of Ph.D.-level scientists and engineers. A careful look at the market for Ph.D.s is necessary to explain why increases in the supply of scientists and engineers with several years of graduate training are still called for even in the face of difficulties in the labor market for Ph.D.s. The key point here is to distinguish between people who are trained exclusively for employment in research universities and people who can work in research and development in the private sector.

Look again at figure 7.6. Events in the Ph.D. market can be summarized in terms of this figure. As noted above, the total flow of students through NSE Ph.D. programs increased starting in the late 1980s and continuing through the 1990s. Much of this flow has been directed at two of the alternatives upon leaving graduate school—university employment and postdoc and other holding positions. The challenge in this area is not to increase the total numbers of Ph.D. degree recipients, but to increase the fraction of them that can put their skills to work in private sector research and development.

This pattern of outcomes—increased numbers of Ph.D. recipients and steadily worsening academic job prospects—can be explained by increased subsidies for Ph.D. training. These subsidies derived from increased support for university-based research, which is complementary to Ph.D. training. As a result, the nature of the support for graduate students changed along with the level. Consider the sample

of students who received their primary means of support for their Ph.D. education from the federal government. Between 1980 and 1995, the fraction whose primary mechanism of support was a traineeship fell from 25% to 15% and the fraction whose primary mechanism was a research assistantship increased from 55% to 63%. The fraction receiving their primary support from fellowships stayed roughly constant at about 10%. Among students whose primary support was from sources other than the federal government (primarily state governments), research assistantships also increased by about 10 percentage points (National Science Board 1998: Chapter 5).

Because this increase in supply consisted of people who planned to pursue academic research appointments, the increased supply of Ph.D. recipients was accompanied by generally worsening job prospects for Ph.D. recipients in the academic market. For example, consider in any year the sample of people with degrees in the natural sciences and engineering who were working in academic institutions and who had received their Ph.D. degree within the previous 3 years. In the early 1980s, there were about 17,000 of these recent degree recipients working in academic institutions. About half of them had faculty jobs. The rest held postdoctoral positions or some other form of appointment. By 1995, this same measure of recent Ph.D.s in academic institutions had increased to 23,000, but the number holding faculty positions remained roughly constant, at about 8,500. The entire increase of 6,000 recent degree recipients is accounted for by increases in nonfaculty appointments (National Science Board 1998: Table 5-29).

The problems in the academic market in the life sciences were documented in a report from the National Research Council (1998). In the last decade, this is the area that has benefited from the most rapid rate of growth of federal research support. Between 1970 and 1997, the median time to receipt of a degree increased by 2 years to a total of 8 years. The number of people who hold a postdoctoral appointment 3 or 4 years after receipt of the Ph.D. increased from 6% to 29% between 1973 and 1995. The fraction of Ph.D. recipients who do not hold a permanent full-time job in science and engineering 5 or 6 years after they have received their degree increased from 11% in 1973 to 39% in 1995. The 1995 data, which were the most recent available at the time that the National Research Council wrote its report, reflect long-term outcomes for the 1989–90 cohort of Ph.D. recipients. Because of the steady increase in the number of degree recipients throughout the 1990s, the competitive pressures in this field have probably worsened still further.

VII. An Interpretation of the Evidence Concerning Higher Education

The picture that emerges from this evidence is one dominated by undergraduate institutions that are a critical bottleneck in the training of scientists and engineers, and by graduate schools that produce people trained only for employment in academic institutions as a side effect of the production of basic research results. This description of the system as a whole hides a heterogeneous mix of different types of institutions. Not all of them will behave according to the description given above.

For example, the pressure to keep enrollments down in the natural sciences and engineering will not be present at institutions that specialize in this kind of training. They may therefore face different kinds of incentives and behave differently in the competition for students. The institution that my son attends, Harvey Mudd College, is one of these specialized institutions, and this may explain why it features information about the market outcomes for its graduates more prominently than traditional liberal arts universities. A quick check of data from other schools is consistent with this observation. MIT and Caltech, two selective schools that also concentrate in science and engineering, present information about median salaries for their undergraduates on the web pages that provide information for potential applicants. Harvard and Stanford, two comparably selective institutions that cover the whole range of academic disciplines, apparently offer no information on their web pages about salaries or enrollments in graduate school.

One natural question that the model outlined here does not address is why competition by entry of more schools like Harvey Mudd, MIT, and Caltech has not partially solved the bottleneck problem described here. Mudd, which is about 50 years old, is a relatively recent entrant in this market, but in general, entry seems to be a relatively small factor in the competition between undergraduate institutions. Presumably the incomplete information available to students and employers about the quality of the education actually provided at any institution is a big factor limiting the entry process, but the nature of competition between schools deserves more careful consideration.

There are also different types of institutions that provide graduate education. The description offered here focuses primarily on graduate education in the sciences, which takes place almost exclusively within institutions where the revenue and prestige associated with research are more important motivating forces than tuition revenue. Training in

these departments differs sharply from the kind of training offered by professional schools where income from tuition is a much more important determinant of institutional incentives. It should not be surprising that, as my research assistant discovered, business schools and law schools follow very different strategies from the ones used by departments of science when they compete for students. In many ways, master's level training in engineering is like these professional schools. Much of the income associated with these programs comes from tuition. Departments that get to keep a portion of this master's level, but not of undergraduate tuition revenue, should therefore be willing to expand the size of their master's programs at the same time that they put limits on the size of their undergraduate programs. These kinds of incentive effects may help explain why master's degree programs in engineering have shown steady growth while undergraduate engineering degrees have not.

In its report on career prospects in the life sciences, the National Academy Board on Biology concluded that policymakers should restrain the rate of growth of graduate students in the life sciences. In my language (not theirs) they also recommended that graduate education in the life sciences be reshaped along lines that are closer to those followed by professional schools. They recommended that students be given more information about career prospects, that they be given training that prepares them for employment in jobs outside of university-based research, and that funds that support the training of graduate students be shifted away from research assistantships and toward training grants or other forms of support that give more control over a student's education to the student.

This last and most controversial recommendation is the one that has the greatest potential to shift the traditional science-based model of graduate education closer to the model that we see in master's level professional schools of tuition-paying customers who collectively can exert a significant degree of control over what happens during the process of education. Similar proposals for modifying Ph.D. training have been made by a variety of study panels. All have received mixed support at best from the scientific community as a whole. (See the discussion of this point in National Science Board 1998: 5-33.)

Opposition to any change in the form of support for graduate education is usually justified in public on the grounds that there is insufficient evidence about what the effects might be for any change in the system of funding for graduate students. A more fundamental

problem—one that goes largely unreported in print but that prominent scientists are willing to justify in private—is that the current funding and training system, one that puts graduate students in the position of apprentices to established scientists and that does not prepare students for careers outside of science, is crucial to the maintenance of the institutions of academic science. Recent work by Scott Stern (1999) offers convincing evidence that recipients of Ph.D. degrees exhibit a strong preference for engaging in the activities in science and are willing to accept substantial wage reductions if doing so will allow them to continue to pursue these activities. This preference could be the result of a selection process that attracts people with this taste into Ph.D. training in science, a training process that cultivates this taste, or a combination of the two. Regardless of the mechanism, any attempt to make the training of Ph.D. students resemble more closely the training of students in business schools could have the effect of significantly undermining the commitment to the ideas and process of science that Stern is able to document. This commitment, which may be psychologically and functionally similar to the commitment induced by training for membership in a religious order or a military unit, may be critical to the preservation of the institutions of science. Unfortunately, it may also help explain why the existing system of graduate education seems so poorly suited to training people for employment outside of academic science. For this combination of reasons, the task of modifying the educational system that trains scientists and engineers may be both very important and very delicate.

VIII. Goals and Programs

To formulate growth policy, policymakers may want to start by distinguishing goals from programs. Goals should be conservative. They should represent objectives that are neither risky nor radical and for which there is a broad base of intellectual and political support. Goals should remain relatively constant over time. They should also imply metrics for measuring success. By these criteria, increasing the long-run trend rate of growth is not specific enough to be a goal. It is appropriately conservative and should be the subject of a broad consensus, but because it is so difficult to measure the trend rate of growth, it does not imply any workable metrics that we can use to measure progress toward the goal. In contrast, increasing the fraction of young people in the United States who receive undergraduate degrees in

science and engineering could qualify as a goal. So could increasing the total quantity of resources that are devoted to research and development.

In contrast to a goal, a program is a specific policy proposal that seeks to move the economy toward a specific goal. For example, the Research and Experimentation tax credit is a specific program that is designed to achieve the goal of increasing the resources used in research and development. It should be possible to judge the success of a program against the metric implied by the goal that it serves. All programs should be designed so that they can be evaluated on a policy-relevant time horizon. If they are, they can also be less conservative and more experimental than the underlying goals. A variety of programs could be tried, including ones where there is some uncertainty about whether they will succeed. If the evidence shows that they do not work, they can be modified or stopped.

To illustrate how this framework could facilitate better analysis of the growth process, it helps to focus on a specific set of hypothetical goals. Imagine that policymakers and the public at large accepted the following goals because they want to increase the long-run rate of growth in the United States. (1) Increase the fraction of 24-year-old citizens of the United States who receive an undergraduate degree in the natural sciences and engineering from the current level of 5.4% up to 8% by the year 2010 and to 10% by 2020. (2) Encourage innovation in the graduate training programs in natural science and engineering. (3) Preserve the strengths of the existing institutions of science. (4) Redress the imbalance between federal government subsidies for the demand and supply of scientists and engineers available to work in the private sector.

Each of these goals suggests natural metrics for measuring progress. The NSF currently measures the fraction of 24-year-olds who receive undergraduate degrees in the natural sciences and engineering (NSE). These data are also available for other countries. Although the United States provides undergraduate degrees to a larger fraction of its young people than almost all other developed nations, many fewer undergraduates in the U.S. receive degrees in natural science and engineering. As a result, the fraction of all 24-year-olds with undergraduate NSE degrees is now higher in several nations than it is in the U.S. The United Kingdom (8.5%), South Korea (7.6%), Japan (6.4%), Taiwan (6.4%), and Germany (5.8%) all achieve levels higher than the 5.4%

level attained in the United States (National Science Board 1998: Chapter 2). The experience in the United Kingdom also shows that it is possible to expand this fraction relatively rapidly over time. In 1975, the figure there stood at only 2.9%.

The indicators for the next two goals will have to be more eclectic. Possible indicators of innovation in graduate education could include the creation of graduate training programs in new areas (bioinformatics, for example) where the private sector demand for graduates is high; or programs that involve new types of training (internships in private firms, perhaps); or programs that offer different types of degrees from the traditional master's or Ph.D. One would also like to see continued strength in the Ph.D. programs that form the core of our system of basic scientific research, measured perhaps by the quality of students that they attract both domestically and from abroad. The second and third goals explicitly allow for the possibility that developments in these two areas need not be closely linked. Universities might introduce new programs in an area such as bioinformatics that train people primarily for work in the private sector without affecting existing programs in biology. The new programs could have the same independence from Ph.D. training in biology that programs of chemical engineering have from Ph.D. training in chemistry. As a result, innovation in the sense of new programs need not imply any changes in the existing Ph.D. training programs and need not take any funding from those programs. If the country makes progress toward the first goal, and the number of U.S. citizens who pursue undergraduate studies in science increases, this could improve the quality of the domestic applicant pool for the traditional Ph.D. programs at the same time that it supplies people to the new alternative forms of graduate education.

It will take new funding from the federal government to encourage the introduction of new training programs and still preserve the strength of existing graduate programs. The last goal sets a rough benchmark that policymakers might use to set expectations for how much funding might be allocated on a permanent basis toward these goals. In the last 2 decades, the primary programs that have subsidized the private sector demand for R&D have been the research and experimentation tax credit, the SBIR program, and the ATP program. Rough estimates of the costs for these programs are \$1 billion each per year for the tax credit and the SBIR program and between \$300 and \$400 million

per year for the ATP program. The fourth goal suggests a starting target of around \$2–2.5 billion per year in subsidies for the supply of scientists and engineers.

If policymakers adopted these kinds of goals, then it would be a straightforward process to design programs that might help achieve them and to evaluate these programs after they are implemented. The following list of programs only begins to suggest the range of possibilities that could be considered. (1) Provide training grants to undergraduate institutions that are designed to increase the fraction of students receiving NSE degrees. (2) Finance the creation of a system of objective, achievement-based (rather than normed) tests that measure undergraduate level mastery of various areas of natural science and engineering. (3) Create and fund a new class of portable fellowships, offered to promising young students, that pay \$20,000 per year for 3 years of graduate training in natural science and engineering.

The details for all of these programs would have to be adjusted based on more detailed prior analysis and as experience with any of them is acquired in practice. Many alternative programs could also be proposed. These three are offered here primarily to indicate the wide range of possibilities and to move the debate about government programs out of the rut in which it has been stuck for some 20 years.

Training grants could be very flexible. They could follow the pattern that has already been established for training grants at the graduate level. Formally, grants could still be given to a lead principal investigator, but in effect, they would offer financial support to a department at a university or college. The details of the proposed training program would be left open to the applicants. Like all grants, they would be peer reviewed, with fixed terms but renewable. One of the central criteria in evaluating any proposed grant would be some estimates of its cost-effectiveness as measured by the expenditure per additional undergraduate NSE degree granted. At this point, undergraduate institutions in the United States award about 200,000 NSE degrees each year. The vast majority (roughly 95%) of these degrees are awarded to U.S. citizens. It will take an increase of about 100,000 NSE degrees to U.S. citizens per year to meet the goal of having 8% of 24-year-olds receive an NSE degree. If the federal government devoted \$1 billion per year, or about \$10,000 per additional degree recipient as a reward to schools that could increase the numbers of NSE degrees that they award, universities would surely find it in their interest to reverse the existing pattern of discouraging students from pursuing NSE degrees. Existing

liberal arts universities could reallocate resources internally. Specialized science and engineering schools could use these funds to expand. New institutions could enter the educational marketplace.

One of the obvious risks associated with a goal of increasing the number of NSE degrees is the risk that universities would simply relabel existing degrees as NSE degrees or would substantially reduce the content of the NSE degrees that they award. One additional criterion for evaluating training grants would be the presence of metrics that verify whether the quality of the degree from the recipient institution is being eroded. But eventually, it would be more efficient to have objective, national measures of student mastery of science rather than the kind of implicit, idiosyncratic, institution-specific assurances of the quality that universities now provide. The model for this system of measures would be the advanced placement tests offered to high school students by the College Board. This organization has shown that it is possible to construct reliable tests with the property that when teachers teach to the test, the students actually learn the material that they should learn. Just as the AP system is guided by high school and college educators, one would expect that any such system for measuring undergraduate achievement in science would be guided primarily by the professors who teach science at the undergraduate and graduate level. Presumably, scores on these kinds of achievement-based exams would not replace other indicators like course grades, letters of evaluation, and general measures of intellectual ability such as are provided by the existing graduate record exams. Nevertheless, they would provide a new and useful piece of information about performance by individual students, by different educational institutions, and by the nation's educational system as a whole. Given the pervasive problems of incomplete information in higher education, it would surely be of value to students, employers, and faculty members to have access to objective measures of what students actually learn.

The new fellowship program is intended primarily to encourage the process of innovation in graduate education by providing a ready pool of funds that could be spent on any attractive new programs that are created. It would also create additional incentives for students to pursue undergraduate NSE degrees. Possible details for such a program could be as follows: The government could select a sample of graduating high school students who show promise in science, say the more than 100,000 high school students per year who pass the advanced

placement exam in calculus. It could offer to a randomly selected treatment subgroup a fellowship that will pay \$20,000 per year for 3 years of *graduate* education in natural science or engineering if the student receives an undergraduate NSE degree. (There would be little reason to pay them a subsidy for undergraduate education. Virtually all of these students already go on to get an undergraduate degree.) Granting the award before they begin their undergraduate study would allow them to take the science courses that prepare them for graduate study. Because the treatment group would be randomly selected, it will be easy to verify whether these grants increase the likelihood that a student receives an undergraduate NSE degree. One could also look among the students who continue their studies in graduate school and see whether the recipients of the portable fellowships select career paths that differ from the students who are supported under the existing RA and TA positions. To the extent that fairness is a concern, one could give some other award to the students in the control group, a new personal computer perhaps.

These fellowships would be portable both in the sense that they could be used to pay for training in any field of natural science and engineering and in the sense that they could be used at any institution that the student selects. Some of the students who receive these fellowships would no doubt pursue a traditional course of Ph.D. study, but some may be willing to experiment with other kinds of degrees. Because these funds would represent new funds, not subtractions from the funds that are already used to support graduate students, and because they would only cover 3 years of training, they should not pose much risk to the traditional training system in basic science.

If the government paid for a total of 50,000 of these fellowships each year, or about 16,700 for each annual cohort of students, this would represent an annual expenditure of about \$1 billion. (To pay for 16,700 new fellowships each year, the government would presumably have to offer many more because the take-up rate would be less than 100%.) It is possible that the availability of these funds would not lead to the introduction of new courses of study that cater to the recipients. If this were the outcome, the fellowships would be judged a failure and would presumably be discontinued. But, *a priori*, it seems quite likely that a flow of funds of this magnitude would induce at least some innovative response from our educational system. It should not take many years of observation to verify whether this conjecture is correct.

IX. Conclusions

The analysis here is driven by two basic observations. The first is that better growth policy could have implications for the quality of life in all dimensions that are so large that they are hard to comprehend. The second is that in the last several decades, the efforts that our nation has undertaken to encourage faster growth have been timid and poorly conceived.

We owe it to our children and their children to address questions about growth policy the way we would approach a major threat to public health. We must use the best available evidence and careful logical analysis to frame new initiatives. We must then be willing to run experiments and to see what actually works and what does not.

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7 Appendix C

Process, Responsibility, and Myrons Law

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12

Process, Responsibility, and Myron's Law

Paul Romer

In the wake of the financial crisis, any rethinking of macroeconomics has to include an examination of the rules that govern the financial system. This examination needs to take a broad view that considers the ongoing dynamics of those rules. It will not be enough to come up with a new set of specific rules that seem to work for the moment. We need a system in which the specific rules in force at any point in time evolve to keep up with a rapidly changing world.

A diverse set of examples suggests that there are workable alternatives to the legalistic, process-oriented approach that characterizes the current financial regulatory system in the United States. These alternatives give individuals responsibility for making decisions and hold them accountable. In this sense, the choice is not really between legalistic and principle-based regulation. Instead, it is between process and responsibility.

The Dynamics of Rules

The driving force of economic life is the nonrivalry of ideas. *Nonrivalry* means that each idea has a value proportional to the number of people who use it. Nonrivalry creates a force that pushes for increases in the scale of interaction. We see this force in globalization, which relies on flows of goods to carry embedded ideas to ever more people. We see it in digital communication, which allows the direct sharing of ideas among ever more people. We see it in urbanization, which allows us to share ideas in face-to-face exchanges with ever more people.

A new slant on an old saying expresses the updated essence of nonrivalry of a technological idea: give someone a fish, and you feed them for a day; teach someone to fish, and you destroy another aquatic

ecosystem. This update reflects what has happened throughout most of human history and warns that we need more than new ideas about technology to achieve true progress.

We need to broaden our list of ideas to include the rules that govern how humans interact in social groups (rules like those that limit the total catch in a fishery). *Rules* in this sense mean any regularities of human interaction, regardless of how they are established and enforced. Finding good rules is not a one-time event. As academics, policymakers, and students of the world, we need to think about the dynamics of both technologies and rules.

To achieve efficient outcomes, our rules need to evolve as new technologies arrive. They must also evolve in response to the increases in scale that nonrivalry induces. Finally, and perhaps most important, they also need to evolve in response to the opportunistic actions of individuals who try to undermine them. Myron Scholes once captured this last effect in a statement he made in a seminar, a statement that deserves to be immortalized as Myron's law:

Asymptotically, any finite tax code collects zero revenue.

His point was that if there is a fixed set of rules in something like a tax code, clever opportunists will steadily undermine their effectiveness. They will do this, for example, by changing the names of familiar objects to shift them between different legal categories or by winning judicial rulings that narrow the applicability of the existing rules.

In sum, rules have to evolve in response to three distinct factors—new technologies, increases in the scale of social interaction, and opportunistic attempts at evasion. Any social group has higher-level rules—*metarules*—that determine how specific rules evolve. The metarules that govern the tax code, for example, allow for changes through legislation passed by Congress, regulations written by the Internal Revenue Service, and rulings handed down by courts. In some domains, the three forces that call for more rapid change in the rules may operate with greater force. In those domains, we presumably want to rely on different metarules.

Why Rules Lag Behind

As the number of people who use the Internet has increased, the rules that govern behavior have lagged far behind actual practice. This case

offers helpful illustrations about the general problem that we face ensuring that rules keep up.

New technologies are part of the problem. Digital communication has created many new possibilities for criminal activity that crosses national borders. Our systems of criminal investigation and prosecution, which are based on geographical notions of jurisdiction, are ill-suited to this new world.

Scale also has an independent effect. Email is based on a set of rules that worked well when dozens of academics were communicating with each other. These informal rules were based on norms and reputation, so the Internet protocol and associated protocols for managing email failed to include even the most basic protections. Now that the Internet has scaled from dozens of people to billions, different rules are needed. For example, there is no built-in way for the recipient of an email to be sure about the identity of the sender. In a “spear-phishing” attack, an email is carefully tailored to resemble the authentic emails that the recipient normally receives. Because none of the usual warning signs are present (there are no offers of millions of dollars stranded in a stranger’s bank account), the recipient is more likely to open an attachment with malicious code. Even RSA, a company whose business revolves around computer security, was compromised through this kind of attack.

Engineers at the Internet Engineering Task Force, a loosely defined voluntary organization with little formal authority, are the rule setters for the Internet. In 1992, they began to work on improving security protocols. They devised a patch called IPsec that reverse-engineered some basic security measures into the existing protocol. They also developed an update to the basic Internet protocol, known as IPv6, that has built-in support for IPsec. The basic specifications for these protocols were completed in 1998. Unfortunately, larger scale not only creates the need for better security but also makes it much harder to implement a change in the rules. The adoption of both sets of protocols has been held back by coordination problems among large numbers of users and vendors.

Even if these protocols are widely adopted, new attacks will still emerge. Bigger scale means that traditional mechanisms like reputation no longer operate and that more people are working to undermine and subvert all the existing security measures. Because a new vulnerability is a nonrival good that can be shared among predators, an increase in scale

can increase the rate at which predators circumvent any given security system.

Financial Markets

Rules in financial markets need to evolve for all of the reasons identified above. Technology is creating entirely new opportunities—for example, in high-frequency electronic trading systems. The scale of financial markets continues to grow, and private actors in these markets will surely seek clever ways to evade the intent of existing rules. The gains from opportunism in these markets are so large that the total amount of human effort directed at evading the rules will presumably be at least as large as that devoted to a low-return activity like cybercrime.

Electronic transactions were supposed to offer liquid markets and unified prices that can be accessed by everyone, but they have not lived up to this promise because they have also created new opportunities for manipulation. For example, some firms now submit and withdraw very large numbers of electronic quotes within milliseconds in a practice known as *quote stuffing*. It is not clear what the intent of these traders is, but it is clear that any electronic trading system will have capacity constraints in computation and communication. Any system will therefore be subject to congestion. In the May 2010 stock market flash crash, congestion added to the anomalous behavior that firms were observing, and this apparently encouraged many high-frequency traders to stop trading, at least temporarily. This seems to have contributed to the temporary sharp fall in prices.

Quote stuffing could be one of many different strategies that traders use to influence local congestion and delays in the flow of information through the trading system. These, in turn, could affect liquidity, as they did during the flash crash. As a result, transactions could take place at prices that depart substantially from those that prevailed just before or just after they occurred.

After an extensive analysis, the Securities and Exchange Commission (SEC) reported that quote stuffing was not the source of the cascade of transactions that overwhelmed the systems during the flash crash. The SEC is still equivocating about whether this particular practice is harmful

and, more generally, about systemic problems that high-frequency traders may be causing. Even if it had tried to address the specific practice of quote stuffing, the type of rule that had first been mooted—forcing traders to wait 50 milliseconds before withdrawing a quote that they had just submitted—would probably have been too narrow to limit the many other strategies that could be used to generate congestion or influence liquidity.

It seems implausible that the kind of behavior that occurred in the flash crash is an inevitable consequence of electronic trading. (But if it is, it seems implausible that the switch to electronic trading has brought net welfare benefits for the economy as a whole.) One year later, it also seems implausible that any of the changes implemented so far has fully addressed the underlying issue. Individual stocks continue to suffer from instances where trades take place at prices that are dramatically different from those that are prevailing seconds before or seconds later.

After the flash crash, trades were canceled if they took place at prices that differed from a reference price by more than a discretionary threshold, set in that particular case as a 60 percent deviation. Under new rules that try to be more explicit, transactions for some individual stocks will be allowed to stand if they take place at prices within 10 percent of the a reference price. In a multistock event, where many prices move together, the band of acceptability widens to 30 percent. Some have criticized these new rules because they still allow some discretion in setting the reference price. Others have expressed concern about the potential for manipulation that could intentionally trigger the looser rules that apply in a multistock event.

As the discussion below about rule making at the Occupational Safety and Health Administration (OSHA) shows, even in a simple setting it is difficult to develop rules in a timely fashion that meet legal standards for clarity and do so following procedures that meet legal standards for due process. The Security and Exchange Commission's attempts to clarify the rules for breaking trades suggest that it is much harder to live up to these standards in a complicated and dynamic context. The SEC seems to have settled for a rule-setting process that leaves ample room for opportunism for extended periods of time. Perhaps some other, less legalistic approach deserves consideration.

Process versus Responsibility in Other Domains

One way to think about how the metarules that govern financial regulation might be adjusted so that the system can respond more quickly is to examine a broad range of social domains and observe the outcomes under alternative metarules. Here are four influential organizations in the United States that set rules and a specific goal that each organization's rules try to promote:

- Federal Aviation Administration (FAA): flight safety
- Federal Reserve: stable economic activity
- U.S. Army: combat readiness
- Occupational Safety and Health Administration (OSHA): worker safety

The Federal Aviation Administration works in a domain with the potential for rapid technological evolution. It has responsibility for passenger airplanes, which are among the most complex products ever developed. It approaches its task of ensuring flight safety with rules that specify required outcomes but that are not overly precise about the methods by which these outcomes are to be achieved. This is one way to interpret what principle-based regulation should look like. In practice, this means that some person must have responsibility for interpreting how any specific act, in a specific situation, either promotes or detracts from the goal that is implicit in the principle. That is, someone has to take responsibility for making a decision.

The general requirement that the FAA places on a new plane is that the manufacturer demonstrate to the satisfaction of its examiners that the new airplane is airworthy. The examiners use their judgment to decide what this means for a new type of plane. Within the FAA, the examiners are held responsible for their decisions. This changes the burden of proof from the regulators of a new technology to the advocates of the technology and gives FAA examiners a large measure of flexibility.

This approach stands in sharp contrast to one based on process. There is no codified process that a manufacturer can follow and be guaranteed that a new plane will be declared airworthy. Nor is there a codified process that the FAA examiners can follow in making a determination

about airworthiness. There is no way for them to hide behind a defense that they “checked all the boxes” in the required process.

One obvious requirement for a plane to be airworthy is that the airframe be sufficiently strong. There are no detailed regulations that specify the precise steps that a manufacturer must use to make a plane strong or show that it is strong. For example, there are no regulations about the size or composition of the rivets that hold the skin on the airframe, nor should there be. On an airplane like the Boeing 787, which is made of composite materials, there are no rivets. Instead, as part of the general process of establishing airworthiness, the employees of the FAA have technical expertise in areas like materials science and testing procedures and are responsible for making a judgment about how to test a particular design and determine whether it is sufficiently strong.

Moreover, because new information about an airframe can emerge for decades after it enters into service, the granting of a certificate of airworthiness is always provisional. Operators of aircraft are required to report evidence that emerges over time that might be relevant to airworthiness. At any time, the FAA can withdraw a plane's airworthiness certificate or mandate changes that must be made to an aircraft for it to continue to be airworthy. No judicial proceeding is required. There is no appeal process for an owner that unexpectedly receives an airworthiness directive that mandates an expensive modification. There is no way to get a judge to issue an injunction that would let the plane keep flying because the FAA has not satisfied some procedural requirement.

It is also clear that the rate of innovation in technologies is a choice variable, along with the rate of innovation in the rules. If social returns are maximized when technologies and rules stay roughly in sync, good metarules might require that those who develop new technologies also have to develop the complementary rules before the new technologies can be implemented. A larger plane such as the Airbus 380 will generate more air turbulence in its wake. This means that the FAA has to implement new rules about the spacing between planes that follow each other on a flight path. The FAA will not let a plane like the Airbus 380 fly until the manufacturer has demonstrated the size of its wake and the FAA has had time to put in place new systemwide rules about separation. This is the polar opposite of the approach that the SEC takes with regard

to the introduction of major changes in the architecture of the electronic trading system.

The FAA implements a system based on individual responsibility by organizing itself as a hierarchy. People at a higher level can promote and sanction people at lower levels based on how well they do their jobs. At the top of the hierarchy, the secretary of transportation and the administrator of the FAA are appointed by the president and confirmed by Congress, both of which are held accountable by the electorate.

The Federal Reserve, like every other central bank, is also organized as a hierarchy. Its leaders are held accountable by democratically elected officials who specify a mandate. In their day-to-day decisions, the employees at lower levels in the hierarchy have a lot of freedom to take actions that will achieve the organization's mandate. They are rewarded or punished based on the judgment of those one level higher in the hierarchy. There is little scope for the legislature to micromanage decisions, and there is no judicial review of the process by which decisions are made. As was seen in the financial crisis of 2009, this kind of system allowed for a much quicker response than the parallel mechanism involving legislation passed by Congress. The Fed's response to the failure of Long Term Capital Management also showed that it could manage what amounted to a bankruptcy reorganization far more quickly than a court could.

Like the Fed and the FAA, the U.S. Army is run as a hierarchy, with accountability at the top to elected officials. After a period during the 1970s when racial tensions in the army were seriously undermining its effectiveness, the leaders of the army decided that better race relations were essential for it to meet its basic goal of combat readiness. In less than two decades, they remade the organization. Writing in 1996, the sociologists Charles Moskos and John Butler observed that among large organizations in the United States, the army was "unmatched in its level of racial integration" and "unmatched in its broad record of black achievement" (2). To illustrate how different the army was from more familiar institutions such as the universities where they worked, Moskos and Butler (1996, 3) tell this story:

Consciousness of race in a nonracist organization is one of the defining qualities of Army life. The success of race relations and black achievement in the Army revolves around this paradox. A story several black soldiers told us at Fort Hood,

Texas, may help illustrate this point. It seems that one table in the dining facility had become, in an exception to the rule, monopolized by black soldiers. In time, a white sergeant came over and told the blacks to sit at other tables with whites. The black soldiers resented the sergeant's rebuke. When queried, the black soldiers were quite firm that a white soldier could have joined the table had one wished to. Why, the black soldiers wondered, should they have to take the initiative in integrating the dining tables?

The story has another remarkable point—that a white sergeant should take it on himself to approach a table of blacks with that kind of instruction. The white sergeant's intention, however naive or misdirected, was to end a situation of racial self-segregation. Suppose that a white professor asked black students at an all-black table in a college dining hall to sit at other tables with whites. This question shows the contrast between race relations on college campuses and in the army.

The system in the army makes such individuals as the sergeant in this story responsible for the state of race relations in any unit they supervise. This system holds them responsible for both their decisions and accomplishments, through occasional ad hoc review of their decisions by superior officers and through more formal decisions about promotion to a higher rank. Any particular decision like that of the sergeant in the story could easily be second-guessed, but the system as a whole has clearly been effective at achieving both integration and good race relations. Both direct judicial intervention in the operation of public school systems and the combination of legislation and regulations that guide behavior on university campuses have been far less successful.

The approaches to safety at the FAA, to macroeconomic stabilization at the Fed, and to race relations in the army all stand in sharp contrast to the legalistic, process-centered approach to safety followed by OSHA. To improve safety on construction sites, which have a bad safety record, OSHA follows a detailed process that leads to the publication of specific regulations such as these:

1926. 1052(c)(3)

The height of stair rails shall be as follows:

1926. 1052(c)(3)(i)

Stair rails installed after March 15, 1991, shall be not less than 36 inches (91.5 cm) from the upper surface of the stair rail system to the surface of the tread, in line with the face of the riser at the forward edge of the tread.

1926. 1052(c)(3)(ii)

Stairrails installed before March 15, 1991, shall be not less than 30 inches (76 cm) nor more than 34 inches (86 cm) from the upper surface of the stair rail

system to the surface of the tread, in line with the face of the riser at the forward edge of the tread.

These regulations are enforced by OSHA inspectors, who can issue citations that lead to fines and that can then be challenged in court. The regulations are supplemented by guidance about enforcement. For example, in the early 1990s, someone also added a note in the *Construction Standard Alleged Violations Elements (SAVE) Manual* that guided OSHA inspectors on how to apply these regulations on stair rails:

NOTE: Although 29 CFR 1926.1052(c)(3)(ii) sets height limits of 30"–34" for stairways installed before March 15, 1991, no citation should be issued for such rails if they are 36" maximum with reference to 29 CFR 1926.1052(c)(3)(i).

This change in enforcement patterns avoids the awkward situation in which a 35-inch-high rail could be cited either for being too low or for being too high, depending on when it was installed, although it still leaves a puzzle about why a 38-inch-high rail might still be cited if it had been installed too early.

It is tempting to ridicule regulations like these, but it is more informative to adopt the default assumption that the people who wrote them are as smart and dedicated as the people who work at the FAA. From this, it follows that differences in what the two types of government employees actually do must be traced back to structural differences in the metarules that specify how their rules are established and enforced. The employees at the FAA have responsibility for flight safety. They do not have to adhere to our usual notions of legalistic process and are not subject to judicial review. In contrast, employees of OSHA have to follow a precise process specified by law to establish or enforce a regulation. The judicial checks built into the process mean that employees at OSHA do not have any real responsibility for worker safety. All they can do is follow the process.

One possible interpretation of the regulations about stair rails is that the regulations once specified a maximum height of 34 inches and that new evidence emerged showing that a higher rail would be safer. As they considered new rules they could propose, the regulation writers faced the question of what rules to apply to stairways that had been installed in the past. Rather than make an ex post change to the regulations for existing stairs, they may have chosen instead to stick to the principle that the regulations that were in force when a stairway was installed would

continue to apply to that stairway but to suspend enforcement for some violations.

The caution about ex post changes in the regulations may derive in part from a concern about judicial review of the new rules. Or it could have come from a concern about judicial review of penalties that had already been assessed or violations under the old rules that would no longer be violations under the new rules. The change in enforcement at least made sure that no judge saw cases where 35-inch-high rails were sometimes cited for being too high and sometimes for being too low.

You can get some sense of how difficult it is to be precise in writing rules by digging into an area like this. From published inquiries that OSHA received, it seems that the decisions here were complicated by ambiguity about the rules for handrails, which a person uses as a grip and should therefore not be too high, and stair rails, which mark the top of a barrier designed to prevent falls and which therefore should not be too low. The top of a stair rail might be but need not be a handrail. It looks as though the rules morphed over time to distinguish more explicitly between the two types of rails.

It is striking that safety officers for construction firms who wrote to OSHA for clarifications about apparent discrepancies between different sections of the regulations waited four to six months to receive answers. (One wonders what happened at the construction sites during those many months.)

Even more striking is the fact that the rules cited here were first proposed in 1990 or 1991, but judging from a 2005 notice in the *Federal Register* calling once again for comments, they did not come into force until sometime after 2005. (The notice in 2005 makes a brief reference to other agency priorities that took precedence over the rules for stair rails.) This required the application of a further enforcement instruction that a stair rail that conforms to the proposed regulation for stairs built after 1991 but that violates the existing regulations (which were not changed for another fifteen years) would be treated as a de minimus violation and would not result in an enforcement action.

The principle-based approach to the regulation of air safety lacks all of the procedural and legal protections afforded by the process of OSHA, but in terms of the desired outcomes, the FAA approach seems to work better. Air travel is much safer than working on a construction site. The

Fed and the army also seem to have been much more effective in addressing complicated challenges. Despite the more extensive judicial protections afforded the construction firms under the OSHA process, firms find the process infuriating. Construction sites are still very dangerous places to work.

Conclusion

People from the United States take pride in a shared belief that theirs is “a nation of laws, not of individual men and women.” Taken literally, this claim is nonsense. Any process that decides what kind of planes can carry passengers, what to do during a financial panic, how people of different races interact, or how a construction site is organized will have to rely on decisions by men and women.

Because of combinatorial explosion, the world presents us with a nearly infinite set of possible circumstances. No language with a finite vocabulary can categorize all these different circumstances. No process that writes rules in such a language can cover all these circumstances. Laws and regulations always require interpretation. Giving judges a role to play in making these interpretations or reviewing them does not take people out of the process.

We could have a system in which individual financial regulators have the same kind of responsibility and authority as the sergeant in the cafeteria. If they saw behavior that looked harmful to the system, they could unilaterally stop it. We could have a system like the one we use to certify passenger aircraft, in which the burden of demonstrating that an innovation does not threaten the safety of the entire trading system rests on those who propose the innovation. In such a system, the people that the innovators would have to persuade could be specialists who would have the same kind of responsibility and authority as FAA examiners. The opportunists in the financial sector would presumably prefer to stay with an approach that emphasizes process, but this leaves the other participants in the sector at a relative disadvantage. More seriously, it leaves those outside the sector unprotected, with no one who takes responsibility for limiting the harms that the sector can cause.

The right question to ask is not whether people are involved in enforcing a system of rules but rather which people are involved and which

incentives they operate under. There may be some contexts where a legalistic approach like that followed by OSHA and the SEC has advantages, but we need to recognize that this approach is not the only alternative and that it has obvious disadvantages.

A careful weighing of the costs and benefits will involve many factors, but the factor that seems particularly important for the financial sector concerns time constants. As the OSHA example suggests, the legalistic process is inherently much slower than a process that gives individuals more responsibility. Moreover, clever opportunists can dramatically increase the delays and turn the legalistic approach into what Phillip Howard (2010) calls a “perpetual process machine.”

Under this approach, rules for the financial sector will never keep up. The technology is evolving too quickly. The scale of the markets is enormous and continues to grow. There may be no other setting in which opportunism can be so lucrative. It is hard to understand why technologically sophisticated people devote any effort to committing cybercrime when the payoffs from opportunism in financial markets seem to be so much larger. If we persist with the assumption that a legalistic rule-setting process is the only conceivable one we could use to regulate financial markets, then the opportunists will thrive. We will settle into a fatalistic acceptance of systemic financial crises, flash crashes, and ever more exotic forms of opportunism.

“No one can predict how complicated software systems will behave” (except in airplanes). “You can’t change behavior” (except in the army). “Financial systems are just too complicated to regulate” (except in countries like Canada, where instead of running a process, regulators take responsibility).

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Chairman YARMUTH. Thank you.

I would now recognize the Honorable Wince-Smith for five minutes.

Please unmute your mic and proceed.

STATEMENT OF THE HON. DEBORAH WINCE-SMITH

Ms. WINCE-SMITH. Chairman Yarmuth, Ranking Member Womack, and Members of the Committee, thank you for the opportunity to appear before you today.

I have the privilege of representing the Council on Competitiveness, a nonpartisan leadership organization of CEOs, university presidents, labor leaders, and national laboratory directors, all committed to advancing U.S. competitiveness in the global economy and raising the standard of living for all Americans through increases in productivity and economic growth.

Since 1986, the Council has championed the federal role in innovation and advocated for measures that could generate greater returns to the nation from its public investments in research and development, in people, and in infrastructure.

As we have heard, for 75 years, the federal government has fulfilled the vision articulated in Vannevar Bush's seminal report, "Science: The Endless Frontier," sowing seeds for the innovation- and technology-driven productivity gains that propelled our country to global economic leadership, generated unprecedented wealth for Americans, drove social progress, and ensured our national security.

However, two decades into the 21st century, the global environment for leveraging science and technology for inclusive economic gain, social benefit, and national security has fundamentally changed, and our nation needs a new game plan.

First, we compete in a multipolar science and technology world. In 1960, the U.S. dominated technology due to the size of our investment, 69 percent of global R&D. The U.S. share has dropped to 28 percent, and China's has risen to 26 percent.

Second, great revolutions in science and technology, such as biotech, AI, and nanotechnology, coupled to the new phase of the digital revolution, are colliding and converging simultaneously. These technologies are reshaping the global economy, society, and all dimensions of our lives as we speak. They will disrupt industries, markets, and jobs. And they pose profound implications for our country's economic prowess and national-security capabilities.

Third, China has set its sight on world leadership in these technologies. It has launched a full-force, richly funded, licit and illicit campaign to achieve this goal, pursuing aggressive plans to dominate every single strategic critical technology at the heart of President Xi's "civil-military fusion" imperative.

In response, the Council on Competitiveness has convened a multiyear national Commission on Innovation and Competitive Frontiers, comprising more than 60 CEOs, university presidents, labor leaders, and national laboratories, led by our distinguished board of directors. Over the past few months, this commission community has deliberated and identified nine priorities that the commission will initially address, five of which are directly linked to the federal role in research and development.

One, our economic and military leadership depends on securing capabilities in these strategic critical technologies. This includes preserving and leveraging, in partnership with industry, the world-class assets of our universities, our national laboratories, and ensuring our entrepreneurial emerging companies can move from startup to scale-up—all part of this national innovation ecosystem. And we must also launch a new era of strategic partnerships with trusted allies around the globe.

The federal investment in R&D as a percentage of gross domestic product has been on steady decline. And we have already all spoken about this. So I ask you, Mr. Chairman and Mr. Ranking Member, is this a new Sputnik moment?

Two, we must strengthen U.S. resiliency. The COVID-19 crisis and virus economy has exposed key weaknesses, such as fragile supply chains that focus more on cost and efficiency and not on resiliency and security. And we have a lack of control over the production and distribution of items critical to the health and security of our citizens. We must harness advanced technologies, from digital systems to drones, to make every level of our society and systems more resilient, more adaptive, and more cyber-secure.

Three, the proverbial valley of death continues to be a major bottleneck in the U.S. innovation system and a barrier to accelerating the rate and scope of U.S. innovation, as it prevents many innovations, as I have said, from startup to scale-up. Many never reach the marketplace. They are vulnerable to foreign acquisition and bankruptcy. China is shopping now, with an unlimited checkbook, for valuable IP, know-how, and people.

Four, we must amplify university and national lab technology transfer, commercialization, and industrial engagements and, to move beyond bureaucratic barriers, ensure that missions and cultures align with this imperative.

And, five, too many citizens and communities are disconnected from the nation's innovation enterprise, with just 10 states accounting for two-thirds of R&D spending, U.S. high-tech hubs just on the coast. And we need to see a diversity of venture capital funding, as well as ensuring that women and minorities engage in this system.

I look forward, Mr. Chairman and Committee, for your questions and to sharing the results of the first stage of our innovation imperative when we release this in December this year.

[The prepared statement of Deborah Wince-Smith follows:]

Testimony of Deborah L. Wince-Smith, President and CEO
 Council on Competitiveness
 Before the Committee on the Budget
 U.S. House of Representatives
 Hearings on Fueling American Innovation and Recovery:
 The Federal Role in Research and Development
 July 8, 2020

Chairman Yarmuth, Ranking Member Womack, and Members of the Committee, thank you for the opportunity to appear before you today to discuss the role of Federal research and development in fueling U.S. innovation and economic growth.

I have the honor and privilege of representing the Council on Competitiveness, a non-partisan leadership organization of corporate CEOs, university presidents, labor leaders, and national laboratory directors committed to advancing U.S. competitiveness in the global economy, and a rising standard of living for all Americans. Since its founding in 1986, the Council has explored the Federal government role in innovation, and advocated for measures that could generate greater returns to the Nation from its public investments in R&D.

For 75 years, the Federal government has fulfilled the vision articulated in Vannevar Bush's seminal report *Science: The Endless Frontier*, sowing seeds for the innovation and technology-driven productivity gains that propelled the United States to global economic and geopolitical leadership, generated unprecedented wealth for Americans, and drove social progress. However, two decades into the 21st century, the global environment for leveraging science and technology for economic gain and social benefit has fundamentally changed, as laid out in the Council's *2018 Clarion Call for Competitiveness*.

The United States Faces New Competitive Realities

The United States now competes in a multi-polar science and technology world. In 1960, the United States dominated global R&D, accounting for an estimated 69 percent share.¹ The United States could drive developments in technology globally by virtue of the size of its investment. But, as other nations have increased their R&D investments and capacity for innovation, the U.S. share of global R&D spending has dropped to 28 percent in 2018, and China, for example, has risen to account for 26 percent.² This has diminished the U.S. dominance and leverage over the direction of technology advancement. U.S. R&D investment as a percent of GDP ranks 10th in the world, behind major U.S. competitors such as Korea, Taiwan, Japan, and Germany.³

¹ Effective Partnering: A Report to Congress on Federal Technology Partnerships, U.S. Department of Commerce, Office of Technology Policy, 1996.

² Main Science and Technology Indicators, OECD.

³ Ibid.

Disruptive technologies are reshaping the economy and society. Humanity stands in the midst of the greatest revolutions in science and technology—biotechnology and gene-editing, nanotechnology, artificial intelligence, autonomous systems, and a new phase of the digital revolution characterized by vast deployment of sensors, the Internet of Things, and the big data tsunami. Each of these technologies is revolutionary and game-changing in its own right. But they are now colliding and converging on the global economy and society simultaneously, with profound implications for U.S. economic and national security.

Of these technologies, several are expected to transform nearly all aspects of human endeavors—on a scale much like electricity enabled widespread industrialization and the production of a vast array of goods and services; provided the power for the rise of cities, deployment of mass communications and modern transportation systems; and propelled a leap in human productivity.

Digital technologies are now fundamentally integrated into every aspect of human existence, society, and activity—defense, the economy, every industry, health care, the research enterprise, education, communications, critical infrastructure, transportation, personal living, and more. The function of the United States and its society are now totally dependent on these technologies. One needs only consider the role digital technologies have played in the COVID-19 crisis and virus economy—supporting millions of U.S. teleworkers and on-line learners, supporting the on-line purchasing of the homebound population, and the scaling of telehealth—helping prevent the total collapse of the economy and maintain social functioning.

Biotechnologies have transformative potential. A recent study suggests as much as 60 percent of the physical inputs to the global economy could be produced biologically—one-third biological materials, and two thirds produced using biological processes, for example bioplastics. The study also suggests that 45 percent of the world’s current disease burden could be addressed with science conceivable today.⁴

Artificial intelligence is likely to be the defining apex technology of the next 50 years—expected to drive a massive transformation in: all aspects of global commerce and business operations, military systems, health care, education, R&D, infrastructure and energy systems, agriculture, decision-making, the management of cities and transportation, harvesting and managing knowledge from the exponentially growing data universe, and in a wide range of human support systems. And while digital technologies are merging the physical and virtual worlds, AI will make them intelligent.

These technologies will shape the global economy for decades to come. They are disrupting industries around the globe, and altering the patterns of society and many dimensions of our lives. They present vast opportunities for innovations that can drive economic growth, job creation, and higher living standards for every American, as well as provide solutions to many of the global societal challenges we face in health, energy, food production, clean water, and sustainability.

⁴ The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives, McKinsey Global Institute, May 2020.

Continued leadership in these technologies will be essential for the United States to maintain its position as a world economic and military leader, and as the most prolific innovating nation.

China has set its sights on world technology leadership, presenting a growing strategic competitive challenge to the United States. It has launched a full force, richly funded, licit and illicit campaign to achieve this goal. China's investment in R&D reached \$554 billion in 2018, second only to the U.S. investment of \$581 billion.⁵ Its dramatic annual rate of R&D growth has it on a path to soon become the world's largest R&D performer. While the United States still leads in basic and applied research investment, China has surpassed the United States in spending on experimental development by \$70 billion.⁶ It has overtaken the United States in science and engineering publications,⁷ and now lags only the United States in international patents filed.⁸

China is pursuing aggressive plans for every strategic critical technology, backed by hundreds of billions of dollars in investment. It is deploying a multi-pronged strategy to acquire technologies and intellectual property from other countries by both licit and illicit means. This includes building research centers in U.S. innovation hubs, forming partnerships with U.S. research universities and companies, forcing joint ventures for market access, sending students to the United States for academic studies, and pursuing top scientists and engineers globally through well-funded talent recruitment programs. To absorb foreign intellectual property and technology, Chinese authorities have established engineering research centers, enterprise-based technology centers, state laboratories, technology transfer centers, and high-technology service centers.⁹

Believing that the nation that leads in AI will shape a global transformation of the economy, society, human activity, and national security, China's *New Generation of Artificial Intelligence Development Plan* is breathtaking in its scope and ambition, a blueprint for constructing an AI innovation ecosystem that they believe will make China the world's AI leader by 2030. Most striking, they have laid out a vision for deploying AI across nearly all elements of society, and a detailed plan for building and acquiring specific AI technology capabilities.

China is by no means the only country that recognizes technology as the main driver of economic growth and productivity. Many smaller, often overlooked nations have distinctive strategies to build global innovation competency and competitiveness. These alone may not pose a significant threat to the United States but, collectively, can present a challenge to the U.S. economy and national security.

These new competitive realities have profound implications for the United States. Our leadership in technology and innovation is under threat, and we face a period of rapid technological change and economic turbulence. The reorganization of the economy around powerful technologies is inherently disruptive, creating and destroying businesses, markets,

⁵Gross Domestic Expenditure on R&D, OECD Main Science and Technology Indicators.

⁶National Center for Science and Engineering Statistics, National Science Foundation.

⁷The State of U.S. Science and Engineering 2020, National Science Foundation.

⁸Patent Cooperation Treaty Yearly Review 2019, World Intellectual Property Organization.

⁹Foreign Intellectual Property and Technology, Office of the U.S. Trade Representative.

and jobs—as so illustrated by the digital revolution. The impact will be felt across numerous dimensions—economic, employment, and social and community stability; and portions of the U.S. workforce are at risk of displacement, which would result in greater economic inequality.

National Commission on Innovation and Competitiveness Frontiers

What should the United States do to confront these new competitive realities, and safeguard, strengthen, and make the most productive use of our innovation capacity? To answer this question, the Council has convened a high-level National Commission on Innovation and Competitiveness Frontiers, comprised of more than 60 CEOs, university presidents, leaders from our labor community and national laboratory enterprise, chief science and technology officers, and other top executives - as well as a larger community of innovation stakeholders from across the country. As a Commission Co-Chair, I am honored to work with my fellow Co-Chairs: Dr. Mehmood Khan, Chief Executive Officer, Life Biosciences, Inc., and Chairman, Council on Competitiveness; Mr. Brian Moynihan, Chairman and CEO, Bank of America, and Industry Vice Chair, Council on Competitiveness; Dr. Michael Crow, President, Arizona State University, and University Vice Chair, Council on Competitiveness; and Mr. Lonnie R. Stephenson, International President, International Brotherhood of Electrical Workers, and Labor Vice Chair, Council on Competitiveness.

The Commission is a multi-year national effort initially examining challenges and opportunities, and developing a national action agenda in three key core topics at the heart of long-term innovation and competitiveness: developing and deploying at scale disruptive technologies; exploring the future of sustainable production and consumption, and work; and optimizing the environment for the national innovation system.

Over just the past few months, hundreds of experts from our Commission community convened in a major launch conference at Arizona State University and met virtually in nearly 50 on-line working group sessions focused on these core topics. Out of this conference and these dialogues, nine priorities or “pillars” were identified as:

- **Urgent:** Failure to act could create serious, even dangerous consequences for the United States, and the world.
- **Strategic:** They are fundamental to U.S. economic security, and U.S. national security and military strength.
- **Pivotal:** They play a prime and determining role in the scope and rate of U.S. innovation.

Five of these priorities are directly linked to the Federal role in research and development. Working groups are delving deeper, and developing recommendations this summer and fall to address them:

Securing Capabilities in Strategic/Critical Technologies. The fundamental role of emerging technologies in shaping the economy, solving societal challenges, and securing military capabilities and homeland defense, and the private sector’s primary role in advancing these technologies, are erasing the boundary between national security and economic security. U.S.

military capabilities have become digitalized, and rely on the strength of commercial industry and its advances in semiconductor technology. Similarly, the military is increasingly implementing advanced materials, AI, and autonomous systems such as robotic equipment and drones in its operations—all being driven by advances in the commercial sector. For example, while DARPA and the Department of Defense invented many of the seminal AI algorithms, big technology companies such as Google, Amazon, Microsoft, and Facebook have combined these with big data and sophisticated computational infrastructure to become leaders in machine learning. The U.S. energy sector and other segments of U.S. critical infrastructure have become digitalized, and rely on commercial technology advancements. At the same time, strategic U.S. competitors have escalated their efforts in critical technologies to boost both their commercial competitiveness and military capabilities. This tightening symbiosis between national and commercial interests is creating the need for greater integration, coordination, and optimization of U.S. investment in research and technology development.

It is important to note that Federal investment in R&D as a percent of GDP has been on a steady decline for more than 50 years, from a 1964 high of 1.86 percent of GDP—during a period of great challenge, and U.S. scientific and technological ambition during the U.S. space program—to 0.62 percent of GDP in 2018.¹⁰ This is lower than the U.K., Korea, Germany, Russia, and several other U.S. competitors.¹¹ If today's Federal R&D investment as a percent of GDP matched this 1964 height, the investment would be \$400 billion, but was about \$130 billion in 2018.¹² In constant dollars, after the American Recovery and Reinvestment Act spending, total Federal R&D spending has been on a decline, from about \$130 billion in 2010-2011 to \$115 billion in 2018.¹³

Contributing to the advancement of critical technologies are numerous research and technology development centers across the United States, operated or supported by the Federal government. They include the 17 laboratories in the crown jewel Department of Energy National Laboratory System, which house scientific instrumentation and research facilities available to the public and private sector. These innovation assets also include 14 diverse national manufacturing innovation institutes, public-private partnerships jointly funded by government and private industry.

Unfortunately, at some of these premier and globally unique laboratories and facilities, core scientific and technological capabilities are potentially at risk due to deficient and degrading infrastructure. Space in many facilities within the system is old, outdated, even obsolete, with maintenance and repair hamstrung by chronic underfunding.¹⁴

¹⁰ National Patterns of R&D Resources: 2017-18 Data Update, Table 1, National Science Foundation.

¹¹ Main Science and Technology Indicators, OECD.

¹² National Patterns of R&D Resources: 2017-18 Data Update, Table 6, National Science Foundation; Budget of the United States, Historical Tables, Table 10.2.

¹³ National Patterns of R&D Resources: 2017-18 Data Update, Table 6, National Science Foundation.

¹⁴ 2018 Clarion Call, Council on Competitiveness, pp. 7-9.

Strengthening U.S. Resiliency. The COVID-19 crisis and virus economy have exposed key U.S. weaknesses such as fragile supply chains that cracked under stress, lack of control over some supply chains that provide critical supplies to the United States, reliance on China for critical U.S. needs, production inflexibility in the face of sudden surging demand, and no national plan for coordinating Federal and university COVID-19 research. Rather than preparing society and its systems for specific disruption or disaster scenarios, for which there are many, the Council on Competitiveness has long advocated for building the processes, well-trained people, and robust systems that provide the ability to limit the impact and bounce back rapidly from whatever disruption or disaster occurs.¹⁵ The Commission's working groups are taking a close look at resiliency, particularly supply chain issues. However, the Federal government could play a role in advancing technologies such as biotechnology, digital technologies, advanced materials, and autonomous systems which have numerous potential applications that can contribute to building a broad capacity for resiliency at every level of our society and its systems.

Bridging the Valley of Death. The so-called "valley of death" is viewed as a major bottleneck in the U.S. innovation system—an innovation rate limiting step—preventing many potentially valuable innovations from reaching the marketplace or slowing their progress toward commercialization, and barring many start-ups from a pathway to growth. Trapped in the valley of death, these technologies and innovations, and the start-up companies striving to bring them to market are vulnerable to foreign acquisition. Bridging the valley of death is one of the highest priorities in raising the rate of U.S. innovation.

The valley of death is reached when start-ups and other companies do not have the capital needed to prototype, demonstrate, test and validate their innovations, lowering risk and generating the performance and cost data needed to attract commercial financing. This occurs when technologies and innovations arise in the start-up sector, and when they are transferred or "spin-out" from universities into the private sector for application and commercialization. The Federal government, national laboratories, and universities often support research and technology development up to this critical juncture in the innovation life cycle.

Companies that move through the valley of death may reach a second one—when the risk of the technology or innovation has been substantially reduced, but the cost to scale manufacturing has risen substantially. When the capital level required is large, manufacturing frequently is scaled off-shore, and the United States loses substantial returns on its investment in research and development.

To capture the full fruits of the U.S. innovation ecosystem, the United States must bridge both gaps. The Federal government has instituted a few initiatives to help bridge this gap. This includes supporting the Manufacturing USA institutes, and some Federal departments have extended Small Business Innovation Research program funding further into the development life-cycle. Expanding testing infrastructure and test beds where innovators can test,

¹⁵ Transform, *The Resilient Economy: Integrating Competitiveness and Security*, Council on Competitiveness, 2007.

demonstrate, and validate their technologies would be an additional approach as called for in the bi-partisan Endless Frontier Act.

Amplifying University and National Laboratory Technology Transfer, Commercialization, and Industry Engagements. Universities receive \$37 billion in Federal R&D funding.¹⁶ And, increasingly, technology breakthroughs come from universities and start-ups which may have spun-out of university research. For example, universities are driving many of the developments in gene-editing, while software start-ups are driving many of the developments in AI. As companies are moving away from exploratory research toward nearer-term applied R&D that supports business units, they more frequently look outside of the firm for breakthrough innovations. In a recent survey of U.S. manufacturing firms, of those firms that had innovated, 49 percent reported that the invention underlying their most important new product had originated from an outside source.¹⁷ In addition, research universities are increasingly expected to be drivers of economic development, serving as local sources of innovation.

Yet, years after laws were passed and incentives put in place to encourage technology transfer from universities—as well as from national laboratories—with some exceptions, they have underperformed. The technology transfer mission has not penetrated the core of their culture, and often is not treated as a priority. In universities, faculty incentives skew in other directions.

In addition, our crown jewel national laboratories are hamstrung by Federal policies, and a lack of resources both to fulfill their missions and to optimize their contribution in support of U.S. industry and innovators seeking access to a shared national innovation infrastructure. The national laboratories turn away hundreds of promising start-ups and innovators every year due to these constraints and authorization concerns. These laboratories are positioned to play a critical role in future U.S. competitiveness, and need broad support and resources to engage more with U.S. industry.

Industry is market driven, while researchers in universities tend to focus on advancing knowledge and those in national laboratories focus primarily on advancing government missions. Time horizons are often incompatible as the private sector is driven by the fast pace of innovation. Academic researchers want to publish results, and national labs pursue longer-term mission-related developments, while industry wants to keep results proprietary for competitive advantage. Private sector innovation is increasingly multidisciplinary, yet university research remains overwhelming dominated by single discipline, investigator-driven research projects, and reward systems, publication practices, and career paths reinforce that approach. In working with universities, there may be significant intellectual property barriers.

¹⁶ National Patterns of R&D Resources: 2017-18 Data Update, Table 2, National Science Foundation.

¹⁷ Arora A, Cohen W, and Walsh J. *The Acquisition and Commercialization of Invention in American Manufacturing: Incident and Impact*. NBER Working Paper, National Bureau of Economic Research, 2016.

Some have suggested that universities partner more with industry in problem-, challenge-, and opportunity-centered research initiatives and projects. As many emerging technologies are multidisciplinary, and problems and challenges multi-dimensional, these partnerships would focus knowledge and skills from multiple disciplines on solutions and leveraging opportunities. Since such work would have end goals and end users in mind, the technology transfer time gap and, perhaps even the valley of death, could be significantly diminished or avoided. For example, the national laboratories' recent work to help support burgeoning industry efforts in advanced manufacturing, transportation, and materials research—through the High Performance Computing for Energy Innovation Initiative at Lawrence Livermore National Laboratory—seek to build deeper, more impactful engagement attuned to industry needs.

Creating a Diverse and Inclusive U.S. Innovation Ecosystem. The Federal government plays a key role in the diversity and inclusiveness of the U.S. innovation ecosystem through its investments in R&D and STEM education. However, at a time when it is imperative that we expand the scope and rate of U.S. innovation, many communities and U.S. citizens are disconnected from the U.S. innovation ecosystem. U.S. R&D is concentrated in certain U.S. states. Ten states account for two-thirds of U.S. R&D spending, and the top 20 states account for 86 percent of the total.¹⁸ U.S. hubs of innovation and high-technology are largely concentrated on the U.S. coasts. Venture capital investment is highly concentrated in certain geographic regions of the United States—particularly California, New York, and Massachusetts which, together, accounted for 73 percent of venture dollars invested in 2019.¹⁹

Among students from racial and ethnic underrepresented groups who earn bachelor's degrees, there are a number of science and engineering disciplines in which they earn them at rates comparable to white students. However, black, Hispanic, and American Indian/Alaskan Native students graduate from high school and college at lower rates than white and Asian students, and have less engagement in the prerequisite classes needed to pursue a science or engineering degree, creating a relatively smaller pool of these students in college who could pursue STEM studies and degrees. This points to the need to increase the college-going population among these underrepresented groups and to better prepare them in the prerequisites needed for STEM studies.

As a result, technology- and innovation-driven economic opportunity is not spreading to all Americans and to all parts of the country.

The National Commission plans to release its first set of recommendations at the Council on Competitiveness 2020 National Competitiveness Forum in December.

In closing, in confronting these new competitive realities, the United States has significant competitive advantages:

¹⁸ U.S. R&D Expenditures, By State, Performing Sector, and Source of Funds: 2017, National Science Foundation.

¹⁹ National Venture Capital Association 2020 Yearbook.

- We remain the world’s epicenter for disruptive innovation, thanks to our exceptional research infrastructure, and low barriers to entrepreneurs and start-ups.
- We remain the world’s largest investor in R&D, spending \$580 billion on R&D,²⁰ building up a globally unparalleled national stock of science and technology.
- We have unique assets such as our national laboratory system and top research universities.
- We have a superb innovation ecosystem where industry, start-ups, labs, and universities collaborate.
- We stand at the top in terms of patents filed by all countries.
- We have a strong flow of venture capital pouring in to commercialize advanced technologies.

Nonetheless, if the United States does not make needed investments in its future, increase its scope and rate of innovation, its fundamental capacity to grow its economy, create jobs, maintain national security, solve societal challenges, and provide a social safety net will continue to erode—and its geopolitical leadership will be at increasing risk.

I am trained as an archeologist. Around the world and through the millennia—the creation, mastery and use of new knowledge and technology have always been the drivers and determinants of which cultures, societies, countries and economies flourished; had military advantage; gained geopolitical power; and changed the course of history. Will that be the United States in the 21st century?

²⁰ U.S. R&D Increased by \$32 Billion in 2017, to \$548 Billion; Estimate for 2018 Indicates a Further Rise to \$580 Billion, InfoBrief, National Science Foundation, January 8, 2020.

Chairman YARMUTH. Thank you very much for your testimony. I now recognize Dr. Shih for five minutes. Please unmute your mic and proceed.

STATEMENT OF WILLY SHIH, PH.D.

Dr. SHIH. Chairman Yarmuth, Ranking Member Womack, Members of the Committee, thank you for the opportunity to address you today.

Though I teach at the Harvard Business School, I am actually a scientist by training, with two degrees from MIT and a Ph.D. in chemistry from the University of California, Berkeley.

I have been a beneficiary of our country's investments in basic scientific research and engineering post-Sputnik, a time when our heroes were scientists like Jonas Salk or Richard Feynman. I still remember watching the first Telstar transatlantic transmission and the Apollo launches.

And I tip my hat to Dr. Parikh. AAAS's Science magazine is still one of my go-to sources.

Post-World-War-II was marked by great public faith in science. After all, science had won the war, and it wasn't just the atom bomb; it was penicillin, antibiotics, radar, digital computer, the whole field of operations research, and many more. And investments in basic science research led to unquestioned American leadership for decades. And the spillovers into industry and from industry were spectacular. We remember Bell Labs, IBM Research, Fairchild Semiconductor, RCA Sarnoff, Rockwell Science Center, a host of others.

Other countries followed America's lead and invested in basic research because they, too, understood the linkage to innovation, technological, and economic progress. Chinese investments are particularly impressive, but they have been part of a roadmap laid out in the mid-1980's to develop the capabilities needed in a modern economy.

Funding for basic research, particularly at universities, is all about building capabilities. It is about training future generations of researchers. As these researchers flow into industry, they bring those capabilities with them.

It is hard to quantify benefits attached to specific lines of research or projects. Rather, it is the ability to recognize future problems and opportunities. In the 1870's, Louis Pasteur thought he was solving problems with fermentation in the French wine industry, but along the way he invented the modern field of bacteriology. GE Research was initially focused on improving the filaments in lightbulbs but ended up pioneering high-vacuum technology and inventing the vacuum tube, which led to the groundwork for radio and television.

The pandemic has exposed the value of capabilities in our country. The funding for the human genome program and fundamental life sciences research have built unrivaled capabilities in genomics and biotechnology. The U.S. scientific community has led work on vaccines and therapies for COVID-19. We do this better than any other country in the world, and it is because we made those long-term investments in basic sciences in the preceding decades.

But the pandemic has also expressed our nation's reliance on other parts of the world. With this has come the realization we have let our capabilities diffuse away in a wide range of sectors, like semiconductors, electronics, machine tools, and countless others.

So what should we do now? I would like to see more funding for basic research.

I have talked to people on both sides of the aisle who I think agree with that, but let me tell you another story. My late father, when I was growing up, was an economist. And I used to watch him come home from work frustrated, and I told myself, "I am never going to do that. I am going to go into sciences and engineering," OK, which is of course what I did. But you know what? I always ended up working on economic problems because I found out, if you didn't get the economics right, it didn't matter how great the science and engineering were. You had to look at the whole picture.

Basic research needs stable funding that can have patience for long-term results. Since the majority of Federal R&D funding is discretionary spending, it is perennially at risk of getting crowded out by mandatory spending on things like debt service and entitlements.

When I was in high school and had my sights set on science and engineering, the mandatory portion of the budget was 34 percent. It is closer to 70 percent now, as we have heard, and we all know that is not going in the right direction.

So, for sure, more funding for basic research. At the same time, I would love to see incentives to encourage firms to conduct more research, especially applied and translational research. I see great opportunities in manufacturing process innovations as well, things like continuous flow reactors, biomanufacturing, things that would enable American firms to leapfrog competitors.

We could encourage and even fund precompetitive R&D collaborations, where partners work together on a common technology platform with which they intend to independently develop differentiated products downstream. And I included that in my written testimony.

Finally, I have been thinking a lot about another issue. Most prescriptions for rebuilding American competitiveness focus on the supply side, incenting firms to move production to or back to the U.S. I think we need to focus, as well, on the demand side, growing domestic demand in early markets for new technologies as a way of incenting the growth of local supply.

We saw this in the 1960's with DoD and NASA, who bought 60 percent of all the ICs made, which really helped the American semiconductor industry get started. We have seen this more recently with NASA and DoD funding SpaceX, and that gives them the cash-flow to really change the game.

Demand provides economic motivation to manufacturers, and proximity to production is extremely valuable, OK? I think it is also very important for people, because when you have demand in a sector, then it drives students to go there for careers.

Basic science research is at the core of American global leadership. It is why the best and the brightest want to come here and work here. Let's ensure our continued leadership.

Thank you for giving me the opportunity to speak with you today, and I am happy to take questions.
[The prepared statement of Willy Shih follows:]

House Committee on the Budget

Hearing on Fueling American Innovation and Recovery: The Federal Role in Research and Development

July 8, 2020

Testimony of Willy Shih

Harvard Business School, Boston, MA 02163

Chairman Yarmuth, Ranking Member Womack, Members of the Committee, distinguished guests, thank you for the opportunity to address you today.

I am on the faculty of the Harvard Business School, where I have taught for the past 14 years. Prior to that I spent 28 years in industry. I am actually a scientist by training, with two undergraduate degrees in Chemistry and Life Sciences from MIT, and a Ph.D. in Chemistry - Magnetic Resonance from the University of California at Berkeley. I have been a beneficiary of our country's investments in basic scientific research and engineering post-Sputnik, a time where our heroes were the scientists like Jonas Salk or Richard Feynman. I still remember watching the first Telstar trans-Atlantic transmission and the Apollo launches. And I should add a tip of the hat to Dr. Parikh; I went to my first AAAS meeting in 1969, and the AAAS's *Science* magazine is to this day still one of my go to reads when I need an authoritative source.

The post-WWII period was marked by great public faith in science. After all, science had won the war, not only with the atomic bomb, but penicillin and antibiotics, radar, the digital computer, the whole field of operations research. Spurred by Vannevar Bush's *Science: The Endless Frontier* and later the Cold War and Sputnik, investments in basic scientific research led to unquestioned American leadership for decades. And the spillovers into industry, and *from industry* I should add, were spectacular. Bell Labs produced the transistor, photovoltaic cells, the laser, satellite communications, the charge-coupled device; IBM Research produced the magnetic disk drive, the one transistor DRAM, countless innovations in computer architecture,

the UPC barcode. And then there were Fairchild Semiconductor, the RCA Sarnoff Labs, the Rockwell Science Center, the Eastman Kodak Research Labs, the DuPont Experimental Station, Xerox PARC; the list goes on. At the beginning of the 1970s, there were many products that were only made in the United States, and this was because of our scientific and technological leadership.

Other countries followed America's lead and invested in basic research, because they too understood the linkage to innovation, technological, and economic progress. The Europeans, the Japanese, the Koreans, the Singaporeans, the Chinese – they have all seen the value and the importance of such investments, and they have invested accordingly. Chinese investments are particularly impressive, but they have been part of a roadmap laid out in the 1980s to develop the capabilities needed to be a modern economy.

Funding for basic research, particularly at Universities, is about building *capabilities*. It's about training future generations of researchers. As these researchers flow into industry, they bring those capabilities with them. I was talking to the Chair of the Electrical Engineering Department at Stanford last week, and he had a great way of describing why so many innovations come out of graduate research: it's because students don't know what can't be done and are willing to try the seemingly impossible. I told him it was the same reason DARPA has been so successful, they're willing to try the audacious, risky projects, and they give their project leaders the autonomy to fail, but occasionally they land the big winners, like GPS, or electronic design automation, or autonomous driving.

Having said that, it is hard to quantify benefits attached to specific lines of research or projects. The more likely value is the ability to recognize future problems and opportunities. In the 1870s, Louis Pasteur thought he was solving problems associated with fermentation and putrefaction in the French wine industry, but along the way he invented the modern science of bacteriology. The General Electric Research Lab was initially focused on improving the filaments in light bulbs, but ended up pioneering high vacuum technology and inventing vacuum tubes along the way, which led to radio and television.

The pandemic has exposed some excellent examples of the value of capabilities in our country. The visionary funding by NIH, NSF and other agencies for the human genome program and fundamental life sciences research from the late 1970s through today have built an

unrivaled ecosystem of capabilities in genomics and biotechnology. What has been most gratifying to me is to see how the scientific community led by the U.S. has pivoted to work on vaccines and therapies for COVID-19. We see the Broad Institute turning their automated genomics platform almost overnight into a COVID-19 test facility. We see companies like Moderna, who has the leading mRNA vaccine candidate and others who have world-beating capabilities because of those earlier investments in the basic science, those investments in training the young people to feed those companies, from start-ups to established players. We do this better than any other country in the world, and it's because we made the long term investments in basic sciences in the preceding decades.

But the pandemic has also exposed our nation's reliance on other parts of the world for personal protective equipment, medical devices, and generic pharmaceuticals. With this has also come the realization that we have let our capabilities diffuse away in a range of sectors like semiconductors, electronics, machine tools, and many other areas, although Vice-Chair Moulton knows I published a paper warning about this more than a decade ago.

So what should we do now?

I would like to see more funding for basic research through agencies like NIH, NSF, DOE, DOD, and others. I have talked to people on both sides of the aisle who I think agree with that. But let me tell you another story to give you some context. When I was growing up, my late father was an economist, and I used to watch him come home from work frustrated and not particularly enjoying his job. I told myself, "I'm going to go into science and engineering," which is of course what I did. But you know what I found out? I always ended up working on economic problems, because I found if you didn't get the economics right, it didn't matter how great the science and engineering were. You had to look at the whole picture.

My biggest worry today is that basic research needs *stable* funding that can have the patience for long term results. Since the majority of federal R&D funding is discretionary spending, it is perennially at risk of getting crowded out by mandatory spending on things like debt service and entitlements. This is the old fixed costs versus variable costs problem. When I was in high school and had my sights set on science and engineering, the mandatory portion of

the budget was 34 percent. Today it's closer to 70 percent, and as we all know, the economics are not going in the right direction.

So for sure more funding for basic research. At the same time I would love to see incentives to encourage firms to conduct more research, especially applied and translational research that can move scientific advances into products. I see great opportunities in manufacturing process innovations as well – things like continuous flow reactors, process intensification, biomanufacturing, things that will enable American firms leapfrog competitors.

In many fields today—especially those at the frontiers of science and technology—investment needs to bring pioneering discoveries to market are beyond the reach of even the best-funded firms. We could encourage, and even fund pre-competitive R&D, collaborations where partners work together on a common technology platform with which they intend to independently develop differentiated downstream products. The obvious benefit is increased research efficiency, increasing scale and scope while reducing duplication through the pooling of resources and capabilities. Participants share knowledge and mitigate risk, leveraging a larger scale and scope of information, resources, and capabilities across firm boundaries. For firms where the incentive to do research may not necessarily be high, being able to tap into a broader knowledge base widens exploratory activities and the development of new ideas.

Two circumstances, in particular, favor such collaborations: when the scale and complexity of R&D needed to remain competitive outpace individual firms' in-house capabilities, and when the target area for partnering is some distance from downstream product markets, focusing on enabling technologies rather than specific market segments or niches.

One example of such a collaboration was SEMATECH, established in 1987 as a way for U.S.-based semiconductor manufacturers to respond to Japanese competitors. The 14 participants felt that no firm acting on its own could compete effectively, so pooling resources and sharing technology had the potential to increase the effective scale of American industry and to recover market share. The founders agreed initially to contribute in proportion to their revenues for an initial period of five years, and the federal government matched the sum, leading to an overall budget of close to \$1 billion. While SEMATECH has evolved considerably since its founding, the pre-competitive R&D phase cemented U.S. leadership at a crucial time.

NASA's Aircraft Energy Efficiency program of the late 1970s offers an outstanding example of the impact of government participation in such collaborations. It came out of a hearing before the Senate Aeronautical and Space Sciences Committee in the wake of the 1973 Arab Oil Embargo, which painted a dire picture of "immediate crisis condition," "long-range trouble," and "serious danger." The program's objective was to establish enabling technology that aircraft manufacturers could commercialize at their own expense. NASA contracted with Pratt & Whitney and GE to do early-stage research on advanced propulsion systems for subsonic aircraft, with involvement from Boeing, Lockheed, and McDonnell-Douglas. This learning platform proved to be immensely valuable to the companies and U.S. global leadership more broadly. The Experimental Clean Combustor program sponsored early development of the Dual Annular Combustor at GE, which went into the CFM-56 engine, the most commercially successful turbofan engine in history. The Advanced Subsonic Technology (AST) and Ultra Efficient Engine Technology (UEET) Programs helped to advance the basic science and secure long-term global leadership for the U.S. in the large turbofan category. The program was pre-competitive research at its best.

We could encourage the formation of more pre-competitive research consortia as a way of helping to commercialize innovations in critical areas to cement global leadership, perhaps by providing seed money or sponsorship. I would be especially keen to see it in the development of new process technologies, something that could help us leapfrog foreign competitors. Federal funding for pre-competitive collaborations in important new areas could foster or accelerate the development of important manufacturing capabilities in industries that will be important in the future.

Finally, since I told you I now understand the importance of economics, I want to bring up an idea I have been thinking a lot about recently. Most prescriptions for rebuilding American competitiveness focus on the *supply side*, incenting firms to move production to (or back to) the U.S. and then potentially erecting trade barriers to protect resulting higher-cost positions. A more sustainable approach would be to focus on the *demand side*, growing domestic demand in early markets for new technologies as a way of incenting the growth of local supply.

If we look historically at industries in which the U.S. has led—automobiles in the 1920s, computers, telecommunications, integrated circuits (ICs), the Internet, products using the global positioning system (GPS)—large early markets drove consumption and gave American firms

incentives to innovate. These markets were driven by audacious goals and basic research coupled with commercialization. Often, as was the case for ICs and GPS, it was the U.S. military or the space program. In the 1960s, DOD and NASA bought 60% of all the ICs made. A more recent example is NASA and the Air Force securing long-term contracts with SpaceX to deliver payloads to orbit—including Crew Dragon in May—and providing cash flow for the company to develop innovations like reusable vehicles that changed the game in space launch.

Demand provides economic motivation to manufacturers, and proximity to production is valuable for early-stage products for which dominant designs haven't emerged. Close interactions between product developers, manufacturers, and consumers facilitate rapid iterations and product refinements. Having a large home market in which to "practice" is also a significant advantage. As long as consumers will buy interim products as the manufacturer improves its production processes, demand can generate the cash a firm needs to grow, learn, and improve. So strengthening our basic science investments, and then as we look to restarting our economy after the pandemic, using stimulus spending to drive demand for specific technology investments would be a double win in my opinion. This is important as well for people – when there is demand, students will go there for careers.

Basic science research is at the core of America's global leadership. It's why the best and the brightest want to come study here, and work here. Let's ensure our continued leadership. Thank you for giving me the opportunity to speak with you today. I'm happy to take any questions.

Chairman YARMUTH. Great. Thank you very much for your testimony.

We will now begin our question-and-answer period.

As a reminder, Members may submit written questions to be answered later in writing. Those questions and the witnesses' answers will be made part of the formal hearing record. Any Members wishing to submit questions for the record may do so by sending them to the clerk electronically within seven days.

Chairman YARMUTH. Now we will begin questions and answers. I will defer my questioning until the end.

I now recognize the gentleman from Massachusetts, the Vice Chair of the Committee, Mr. Moulton, for five minutes.

Mr. MOULTON. Good afternoon.

I want to thank all the witnesses for testifying but especially the minority witness, Professor Willy Shih, who spent a full semester asking me questions not that long ago in business school. I only get five minutes, but what an honor it is to have those five minutes indeed.

So thank you, Professor Shih, for being here.

And a special thanks to my friend and fellow veteran, the Ranking Member, Steve Womack, for inviting Dr. Shih, for talking about the

[inaudible] in your opening remarks, and for working to come to bipartisan conclusions about the way forward.

And, Professor Shih, I will add, thank you for being such a great professor in my first year of business school that I asked you to advise our independent study in my second year.

We did a financial analysis of the California High-Speed Rail Program. We came to two significant conclusions. One, the project is going to cost a lot more than California says, a conclusion that was borne out soon thereafter when the state raised their cost estimates. And, two, despite the higher costs, it still is a much better investment, at lower cost and higher returns, than the alternative of expanding airports and highways to meet the transportation demand of the next 50 years.

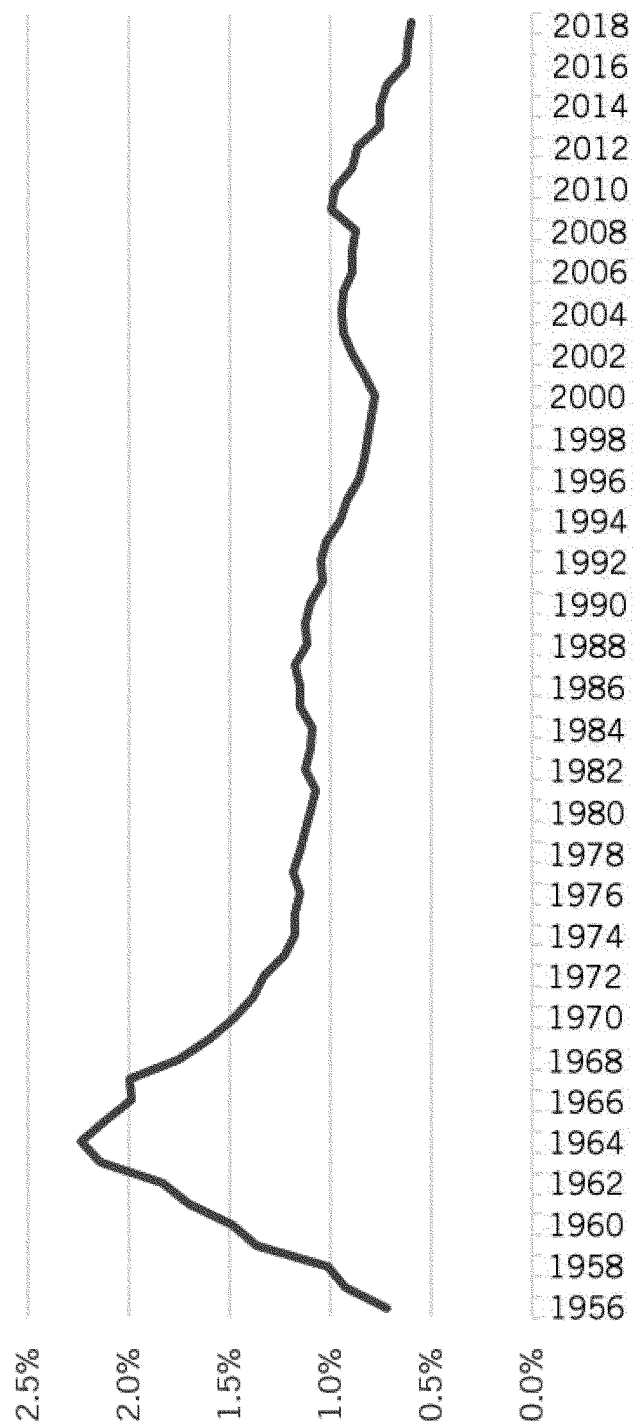
In other words, if you do a cost analysis, the project looks expensive, but if you do a cost comparison, it presents a very different conclusion. And if you do a cost-benefit analysis, as we should be doing in government budgeting, it becomes a no-brainer.

Professor Shih, you have often said that investing in rail is smart because rail is so efficient. And we will get to investing in 21st-century infrastructure versus 1950's infrastructure in a minute, but, first, I want to amplify Chairman Yarmuth's opening remarks with this graph, which specifically shows that federally funded R&D as a share of the U.S.'s GDP is declining.

Sam, please display the second slide in my deck, titled "Federal R&D as a Share of GDP."

[Slide.]

Federal R&D as a Share of GDP



Source: Innovation Technology & Innovation Foundation (ITIF)

Here in Massachusetts, where Professor Shih and I both live, we are quite proud of our biotech industry, the pioneers in creating vaccines and treatments for COVID-19.

Professor Shih, is there any connection between the success of a company like, say, Moderna and the graph that we see here?

Dr. SHIH. Well, absolutely. I mean, I think Moderna is kind of a textbook example, and not only Moderna but a lot of the other U.S. companies that are actively working on this.

What we have seen is a pivot, and what it reflects is the capabilities that have been built up by these very prescient investments in the human genome program going back to the late 1980's, early 1990's and the development of this cluster around Massachusetts and New England.

So it is directly a consequence of the capability development in people, I should add, people who have been trained as researchers. And then, when we had this crisis, those people pivoted from whatever they were doing.

The most gratifying thing I have seen this in this COVID-19 crisis is scientists—anybody who is anywhere close to viral infection and vaccines or pharmacology or, you know, any of the life sciences, we have seen this tremendous pivot, everybody working on an angle of this disease. And it is because we built those capabilities.

And it is just like I was talking about with Louis Pasteur and, you know, what kind of capabilities, so you can recognize, when problems come up, different ways of responding to them. So I think it is directly linked.

Mr. MOULTON. Great.

Sam, if you could just switch the display back to me.

So, Professor Shih, the next thing I would like you to comment on is whether or not it is a problem for America, a competitive threat to our leadership, that China is investing much more in government funding in biotech than we are here in the United States.

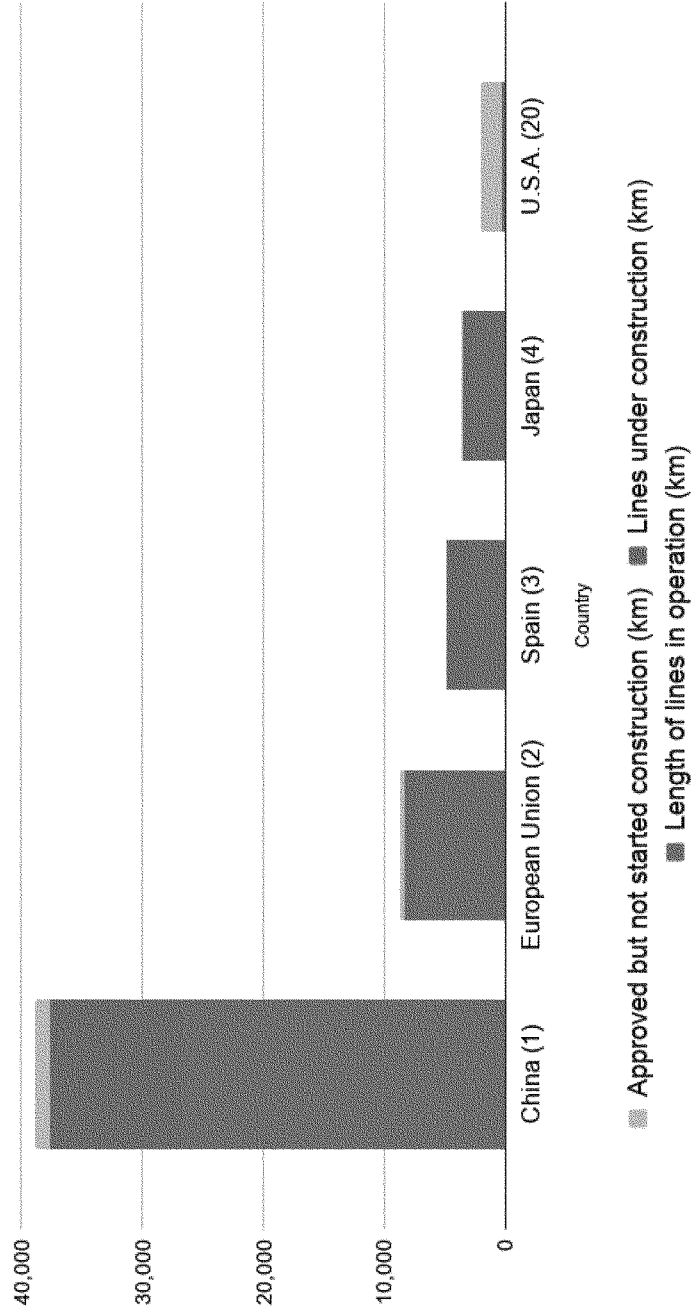
And, Sam, if you would just please display the third slide in my deck, titled "High-Speed Rail By Country."

This same story that we are showing here about high-speed rail could be told for broadband, green technology, or carbon-free nuclear energy.

Sam, you can bring the display back to me.

[Slide.]

High-Speed Rail by Country



Source
International Union of Railways (UIC)

But, Professor Shih, it seems that we are falling behind across the board.

And none of these issues should be partisan. I mean, our conclusions on California high-speed rail were not geared toward a Democratic position or Republican position; they were just math. In fact, I never had any idea about your political proclivities coming into this, Dr. Shih.

But could you talk about what future-focused investments in infrastructure do to create a market for domestic manufacturing?

Dr. SHIH. Well, one of the things I have been thinking about is, just as we saw NASA and DoD created demand for integrated circuits in the 1960's, OK—and, frankly, that is what got the whole integrated circuit industry firms like Texas Instruments off the ground, right? Because there was the demand for that. OK.

And I have seen this in China in many areas, where what they do is they generate demand for a product, and, first of all, what it does is, firms sense opportunity, so they go invest. They go invest in plants and equipment, they invest in R&D. By the way, they compete with each other, OK? But having the demand, bright young people go into it because they see career prospects, OK? So they go into it.

One of the things that my recent research on China has really highlighted is, it is much less of a top-down command-and-control-type model for innovation as well, OK? Because what you see is—you know, Beijing may set some directions. I mentioned they set this, you know, science and technology leadership policy back in 1986. It was called the 863 Program because it was established in March 1986. That is when they laid out this roadmap for capability development. But then you have regions and provinces and cities who say, "OK, you know, government says this. We are going to go invest in these areas." And they compete with each other, OK?

So it has a much more market quality than a lot of people would recognize, in terms of the results they produce. You get a lot of waste, but we see the results in terms of what they have done.

The high-speed rail investment in China is a really interesting example. They have used it, as much because they want it for transportation, to modernize transportation, it is actually a tool for economic development, OK?

I happened to visit the world's most advanced flat-panel factory in Hefei, China, two years ago, and I took the high-speed rail over from Shanghai. And I asked them, I was like, "Why is this factory here?" OK. Now, that is a much longer story. But the fact that you had high-speed rail meant the engineers were commuting from Beijing or commuting from Shanghai, right?

And so there is also an economic-development aspect of this. So it is an interesting combination of things which has led to their leadership, but it is very much driven by this demand side.

Mr. MOULTON. Great.

Thank you very much, Mr. Chairman.

Chairman YARMUTH. With that, the gentleman's time has expired.

I now recognize the Ranking Member, the gentleman from Arkansas, Mr. Womack, for 10 minutes.

Mr. WOMACK. And I thank the Chairman again for hosting this all-important discussion about research and development, particularly in the pandemic phenomenon of where we find ourselves today.

Real quickly, Dr. Shih, you had mentioned in your remarks and picked up on the fact that I gave a lot of attention in my opening remarks to the fact that the deficits and the debt are becoming a chronic problem in our country. And I spoke specifically about the fact of what I call this “big squeeze,” the fact that the mandatory side of our balance sheet is continuously squeezing that discretionary side, where most of this research and development funding, the lion’s share of it, comes from.

And so, if you just kind of project this thing out a few more years and if indeed we don’t find a solution for throttling back the growth of the mandatory programs, this situation is not going to get better. Indeed, it is going to get a lot worse. Would you agree?

Dr. SHIH. Well, that is why I made that comment.

Now, this is not a political persuasion statement. This is just kind of, like, how I grew up. Like, I don’t like to borrow money and stuff like that. OK. But set that aside.

When I was in business, I found that this problem is essentially the fixed-cost/variable-cost part of your budgeting process, OK? And what happens is, when times get tight, everybody cuts all the variable costs because those are the things they can do. OK. But, in essence, what you do is you mortgage your future when you do that. All right?

So, you know, I understand the importance of the mandates. OK. But we look at where there is going, and, you know, I am relying on our leaders, you know, you guys, to be thoughtful about how do we manage this problem. Right? Because we can project where it goes, and, you know, the money has to come from somewhere.

Mr. WOMACK. So I want to go to Ms. Wince-Smith for just a moment on the same subject.

It just is inescapable to me that, if you are not able—it is one thing to defer the maintenance of a road. With increased costs of asphalt, concrete, this sort of thing, labor, yes, if you defer it, it is probably going to become more expensive. But can you talk, from the area of the Council on Competitiveness, delays or deferral of investing in key research? It is not the same as just deferring maintenance on a piece of infrastructure, is it not?

Ms. WINCE-SMITH. Absolutely not.

And let me just say that, in terms of where our investment needs to be in research and development, the basic research has been tremendously important. It will continue to be. It has given us the seed core for the future. But we do have to ramp up, in a major way, our investments in these platform critical technologies that I talked about in my opening statement.

So let me give you an example. We can do a lot of basic research in next-generation microelectronics as we reach the end of Moore’s Law, but if we don’t have a capability to bring together the industrial infrastructure, the suppliers, the ecosystem, and to manufacture at scale here in the United States, we will risk the underpinning for basically the future economy to China. It is a huge issue.

We did this very strategically back when SEMATECH was created. It had DoD investment matched with private-sector, and it changed the game. But we also linked that investment to enforcing our trade laws with Japan and having a regulatory system that also unleashed private-sector capital.

So what I would like to say here is, we have to connect the pieces we have. That is part of the new game plan. We can't just rely on individual investigators and universities. We can't just rely on missions in the national labs; startup companies and big companies now who aren't investing. We have to put all this together in a very strategic way. And the federal government has a huge leadership role to play in setting this strategy in partnership with the private sector.

So if I were asked, what is the one thing we could not afford to lose going forward? It is the leadership in not just the research but in the manufacturing at scale here in the United States of the next-generation microelectronics.

Mr. WOMACK. So one other question for you, and that is: what is the Council's idea or position or thought on the talent demand?

I mean, if you are not investing in the kind of research and development that we all know that we need to be doing, what does that say to the future scientists and engineers that are coming through that pipeline right now about their future career choices?

Ms. WINCE-SMITH. We have to invest in the development of the talent. We have to invest in it starting, you know, in the K-12, all the way up to the highest end of the research enterprise. And we also have to make this far more inclusive. We need to use all of our people in a way that they can contribute to this innovation ecosystem.

So it is very concerning—I mean, I am a woman, of course. It is very concerning that, still, after many years and many programs, we don't see women in the leadership roles in the science and technology enterprise. And, of course, we have, you know, racial issues, as well, in underrepresentation.

So that is a huge issue, and we have to invest. Our departments and science agencies need to invest.

One place where I will say it is being done very, very well is in the military. And I have the fortune to have two sons who came out of the Naval Academy, and I witnessed firsthand how they mentored and developed talent representing our demographics and did it in a way that virtually all of the midshipmen and—women graduate with full engineering degrees. And they make sure that happens.

We have to do that throughout our country now, and it has to be a very high priority. Because without the people, we don't have anything to move forward with.

Mr. WOMACK. Yes. Thank you.

Dr. Shih, back to you for just a minute. It goes without saying that research and development and manufacturing kind of go hand-in-hand. And we've seen this in kind of an unfortunate sort of way during the COVID-19 phenomenon with the ability to produce ventilators, N95 masks, that whole broad range of PPE, basic stuff that you should be prepared to have or be able to create in an emergency that we have not been able to.

Why does a country with such vast resources, such great talent, such amazing innovation struggle to keep the innovation side and the manufacturing side on the same side?

Dr. SHIH. I think it traces back to demand and, in particular, for PPE and ventilators and things like that, stable demand. OK? And what we ended up having is a lot of commoditization pressure from low-cost suppliers in China in particular. OK?

And I was just talking to an Indian pharmaceutical company, because I am looking at the supply chain for pharmaceuticals, because, you know, that was exposed during this pandemic as well. And they said, "Well, we used to be vertically integrated, but then we had the emergence of all these Chinese suppliers who had much lower costs. And if you don't buy your active pharmaceutical ingredients from them, you are not competitive." So they just kind of got squeezed out from that.

We see that, for example, in steel. I never understood why steel could cost 60 percent as much to manufacture in China, or, you know, the XFLB factory price for steel in China could be 60 percent of what it is in the U.S., when you are buying iron ore at world market prices and coking coal at world market prices and energy at world market prices. OK. But some firms have subsidies.

But then the consequence of that, for example, is, if you want to buy a steel shipping container, there are only two manufacturers left in the world, and they are both in China. OK? And it is a consequence of those kind of platform things, which, because they are cost-driven and people won't pay a premium for assured supply, we don't have them in the U.S. OK?

So I would say, you know, we had PPE makers in the U.S. And if we gave them stable demand contracts, that is fine, they would still be around. OK. But, you know, we penalize companies if they have underutilized capacity or they are higher-cost. Right? So it is very hard from a business standpoint to stay in those businesses.

Mr. WOMACK. Yes. Chairman, again, thank you for bringing such an interesting panel, a very qualified panel, to our Budget Committee today. And I am going to yield back the balance of my time and head pretty soon to a Defense markup. Thank you so much.

Chairman YARMUTH. All right. I thank the Ranking Member. His time has expired.

And I now recognize the gentleman from Pennsylvania, Mr. Boyle, for five minutes.

Mr. BOYLE. Thank you, Mr. Chairman.

I also want to thank all the witnesses. I enjoyed listening as well as, before this, reading your written testimony.

Just a quick plug. Two speakers before talked about the investments in high-speed rail. Given that I represent Philadelphia that sits smack-dab in the middle of the Northeast Corridor and am a frequent user of Amtrak myself, I want to echo, any investments that we could make in the United States to go toward high-speed rail and finally join our competitors in Europe and Asia in an area where we greatly lack.

I can tell you how important it is here, locally, to our economy, so much so that, during my time in Congress, it was always an issue that brought together Members of Congress from both the city as well as the suburbs, Democratic and Republican colleagues.

But what I wanted to focus on was manufacturing.

And one of the misperceptions about our economy and manufacturing is the notion that caught on in recent decades that America doesn't make anything anymore and that we had to choose, essentially, this false dichotomy between continuing to be a high-GDP country on the one hand and making things on the other. Germany completely proves that fallacy. Manufacturing makes up a relatively high percentage of that nation's GDP and much higher, indeed, than ours.

I also personally just can't stand the notion that some people have about manufacturing when they seem to picture a 19th-century or early-20th-century factory floor. Anytime I am touring a company locally that is involved in manufacturing, I am always blown away by the technology that is often used in what is considered, quote/unquote, "blue-collar" work.

So it is pretty clear to me, self-evident just even through those tours, the link between research and development and innovation on the one hand and the present as well as the future of manufacturing.

So for Ms. Wince-Smith or Professor Shih, I was wondering if you could speak to that, about the link between the investments that we make in R&D and how we can see that product in terms of manufacturing here in the United States domestically.

Ms. WINCE-SMITH. Thank you, Congressman.

Let me just start by saying that, in my career, some 25 years ago, I worked on the whole imperative for U.S. leadership and manufacturing. And this is when the Japanese were basically in a fierce trade war with the U.S. on many high-tech—

Mr. BOYLE. Right.

Ms. WINCE-SMITH. And I remember one of the Japanese leaders from MITI coming and saying, "You know, we are worried about manufacturing. It is not dirty, dumb, dangerous, and disappearing."

Twenty-five years later, the Council on Competitiveness has articulated in much work that manufacturing is smart, safe, sustainable, and it is surging. And if we don't link the innovation with the manufacturing, we will lose the next generation of innovation.

So I have to share the example of flat-panel displays. Professor Shih mentioned that factory in China. When I was Assistant Secretary at Commerce, we had invented in the United States, including a path from Kodak, every single flat-panel display technology, from liquid crystals, planar, field emitters, the whole thing. We had a plethora of startup companies, and none of them were able to manufacture once they had to buildup a factory at scale because of our capital cost structure.

And this is why we have to bring these issues into this discussion. We have to have long-term, patient capital that is going to go into scale-up of manufacturing.

A123 batteries is a perfect example. Lots of federal investment, major research. Ended up in bankruptcy. And for just a few-million-dollars' bid, over Johnson Controls, China got all the intellectual property, the people, everything. Lock, stock, and barrel, it is in China.

So one thing I do want to suggest as a potential major initiative for the country—I am sure it will be part of the Council’s national innovation strategy—we do need a national infrastructure bank. We do need to have a different financing path going forward. Today, a venture capitalist firm would never invest in Intel. They won’t invest in the deep science manufacturing of the future.

And so this is an issue where we have to work on financing, we have to work on tax incentives.

Just one last little factoid. We have trillions of dollars sitting in hedge funds in Greenwich, Connecticut. They are not investing in any of the things we are talking about here. But we could create incentives, new capital gains, holdings, all sorts of things, to unleash that capital to invest in all the things that we are talking about in this hearing. And if we don’t, I think we are giving away, you know, our future and standard of living to our next generation.

Mr. BOYLE. Thank you.

Chairman YARMUTH. OK. The gentleman’s time has expired.

I now recognize the gentleman from Georgia, Mr. Woodall, for five minutes.

Mr. WOODALL. Thank you, Mr. Chairman, and thank you for holding the hearing. We could do an entire hearing just on what Deborah Wince-Smith raised regarding the vulnerability of IP to foreign acquisition. So much to unpack in here, and I am grateful to you for doing it.

First, Mr. Shih, I want thank you for the years of investment you put into Mr. Moulton. We are all the beneficiaries of your toiling in that vineyard. And I thank you for doing the best you could with what you had to work with in that environment. America thanks you for that.

Dr. Romer, I wanted to go first to your chart about basic science versus technological progress. It is not lost on me that almost every quote in your various testimoneys today on what percent of GDP was going to R&D was different. We categorize these things in different ways. But you clearly are expressing a need to see us move from basic science preeminence back into technological progress preeminence as well.

Does that involve simply additional dollars, as everyone has talked about, or does that also involve reprioritizing the dollars that are going out the door from the federal government today?

Dr. ROMER. So I think a good place to start here is to look back at what worked in the past. So what made us a worldwide power in petrochemicals? It was universities, who created chemical engineering as an entirely new field of study, new schools, a new type of graduate degree. And it was the people produced by universities who then went out and made us a powerhouse.

So I am echoing something that Dr. Shih said, which is that what really matters here are people. And we have forgotten this. We tend to think of the government’s role as to fund papers or patents, and that is what universities produce. But, in the past, where universities were singularly effective in contributing to technological progress was when we rewarded them for producing people who could then go out and raise standards of living, be more productive workers.

One way to recover this would be to go back to what worked in the National Defense Education Act and have funds that are directly allocated to students to pursue courses of graduate education and to go one step further and to say the students are the ones who decide what course of study they will pursue.

Unfortunately, the money that we have has been basically captured by professors doing basic research, so all the support for graduate students goes to professors, who hire research assistants and support graduate students through their grants but to work on the things the professors want to work on. And it means that our system doesn't respond when a bunch of young people see an opportunity that they would like to get trained in and like to go work on.

So I think it is not just more money, but it is spending it in different ways and, in particular, betting on and counting on students, and also not relying on the same degree of centralization at the federal level. Go back to what worked before, which was to count on the competition between 50 universities in 50 states that were all competing to do a better job.

Mr. WOODALL. Well, let's talk about that for a second. Dr. Parikh has a chart, a graph, in his presentation that looks at investment in basic science. And while the government investment over the last 40 years has fallen in half, industry investment has doubled. And so, as a percent of GDP across our nation, unlike a centralized economy like China, we are still expanding. We are just expanding in different ways.

[Charts.]

Leader

Follower

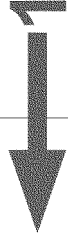
**Basic Scientific
Achievement**

Follower Leader

Technological Progress

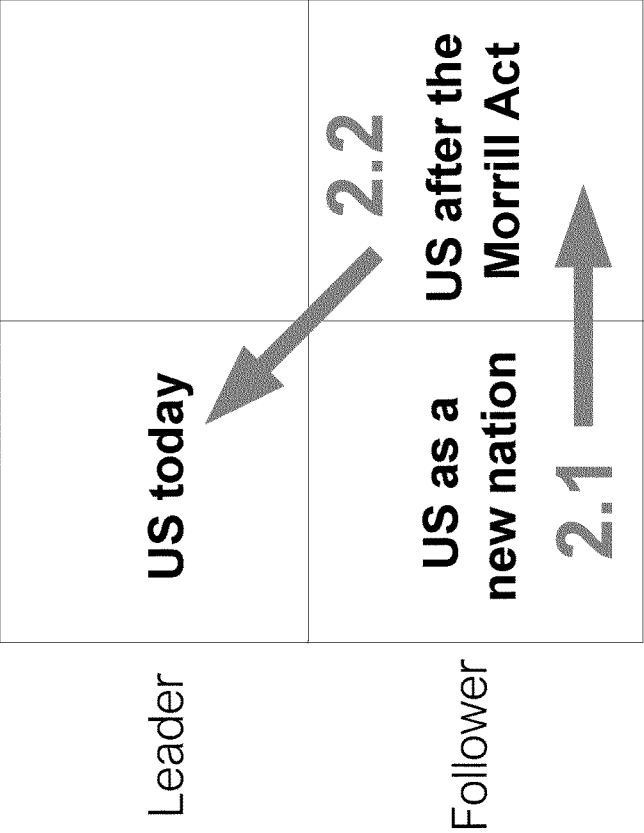
**Basic Scientific
Achievement**

Leader	US today	US after WWII
Follower		



Follower Leader

Technological Progress



Basic Scientific Achievement

Follower Leader

Technological Progress

Dr. Parikh, when you included that chart, are those things created equal? Do we get more of the focus that Dr. Romer was talking about on people and applied sciences when the industry is making those investments? Help me to understand whether that is good news or bad news as you laid it out.

Dr. PARIKH. Yes. It is good news and bad news.

The good news is that industry is very good at development, and when it sees an opportunity to go from a discovery to a product, it does a very good job of finding capital and getting there.

The challenge becomes that people part. There is not as much development of people whenever the development funding is coming from industry. Those people are created in academia; they are created in these graduate programs. And they are the biggest asset.

It is going to take people from everywhere to get cures for COVID, to get cures for cancers. And when we are limited to just development, it breeds just a certain type of person, whether it is the engineer in that one lane or it is the molecular biologist who knows just that one area. It doesn't give us the breadth of backgrounds that really create the innovation and the amazing advances that we see.

Mr. WOODALL. All right.

OK, Mr. Chairman, thank you for the hearing. I yield back.

Chairman YARMUTH. I appreciate that.

The gentleman's time has expired.

I now recognize the gentleman from North Carolina, Mr. Price, for five minutes.

Mr. PRICE. Thank you, Mr. Chairman.

And thanks to all of our witnesses for a very interesting and productive hearing.

I want to maybe start with Dr. Parikh but ask any of you to chime in who wish to. My broad topic, probably what I would have asked before this week, would still involve questions of personnel, the flow of students and post-docs and research fellows from all over the world, the intersection of immigration policy and the research enterprise in this country.

But because it is occurring when it does, this has the feel of another national crisis and certainly a political controversy. I know I have heard from every institution of higher education in my district, research institutions, who are in a near-panic over this: apparently, the intention of the Trump Administration to not let the immigrant students and researchers stay here whose universities, this fall, go to completely—or have to stick completely with online education, which, of course, is a big unknown and certainly throws a lot of questions into how they are going to be able to operate, and not just what the fate of the students is, but what also the universities are to do about this.

So I want to ask you about that incident, this problem in particular. And, of course, it is in the context of a larger question about how immigration policy and the research enterprise, the vitality of the research enterprise in this country, intersect.

I come, as some of you may know, from a very research-rich environment in North Carolina, the Research Triangle area. Higher education and research are our stock in trade. And along with that we have a very diverse and impressive immigrant population, peo-

ple who come in for training and research efforts and then many of whom stay. And so this announcement has sent waves of apprehension and, as I said, near-panic through the higher-education community.

It seems to me that the decision about opening this fall, this is a very, very difficult decision. I think it is going to be. And as the cases spike, it looks worse. I can't imagine that we are helped by adding this element to the decision, to make it more complex by adding in the element of what the effect on international students is, and with the effect on international students, the effect of the projects and the enterprises that they are a part of in the university.

So I would appreciate your comments on this, the effects that the administration policy would possibly have. I am sure you are in touch with institutions; you are hearing, just like I am, what the effects might be. And then any broader reflections on the intersection of immigration policy and the research enterprise I would be interested in as well.

Dr. Parikh, I would like to start with you, but I would be happy to hear from all of our witnesses.

Dr. PARIKH. Thank you, Congressman.

So just to start specifically with the ICE policy announced yesterday, we are very concerned—I am very concerned. Graduate students from around the world populate our laboratories, and, frankly, even though they are students, they are conducting a lot of our research and a lot of our basic research. And so the fact that we are implementing a policy where we might not have them in the laboratory or participating in the research is just—it is bad for America.

Second, it is cruel to the students. These are students who might be here already who might have to go back. It is cruel, and it is just not the right thing to do.

To reflect on immigration policy, I am a second-generation American, and I have the privilege of leading the AAAS. My parents came from India to rural North Carolina, Hickory, North Carolina, you know, in 1968. And that is a story that you will hear from thousands of scientists around this country. And, you know, as Ronald Reagan said, you know, the United States is the one place where you can come from all over and you can be an American. And scientists have proven that.

And 38 percent of the Nobel Prizes awarded to Americans since 2000 have gone to immigrants. You know, the population of post-docs in America, that population who are working in artificial intelligence, who are working on biomedical, who are working on physics, that population is one-third immigrants.

It is self-defeating to create a policy that doesn't continue the fact that America is a crossroads of science.

Dr. ROMER. If I could just comment on this—

Chairman YARMUTH. OK. Go ahead. Briefly, if you can.

Dr. ROMER. Yep.

So we are dependent on foreign talent to make our university research system run. So if you cutoff the supply when you are dependent on a foreign source, you are going to have trouble.

But we should step back and ask, why is it that it is not our goal to be fully self-sufficient in talent, if need be? We benefit a lot from flows of people across borders, but why are we so short on American talent in our graduate programs?

And I think the reality is that we have not made it attractive enough for bright people from the United States to go on in graduate education. And the right kind of fellowship program that puts students in charge in designing and pursuing a graduate career could substantially increase the number of bright U.S. citizens who want to be part of this system.

Chairman YARMUTH. Thank you.

Mr. PRICE. Thank you very much.

Thank you, Mr. Chairman.

Chairman YARMUTH. The gentleman's time has expired.

I now recognize the gentleman from Ohio, Mr. Johnson, for five minutes.

Mr. JOHNSON. Well, thank you, Mr. Chairman, and I appreciate you having this hearing today. It is an important topic.

You know, as a former chief information officer, I understand the importance of research and development and the critical role that the federal government and the private sector play when it comes to fueling American innovation and economic growth.

Thanks to various sectors funding and performing R&D, including the federal government, businesses, state governments, higher-education institutions, and nonprofit organizations, the United States has been for a long time a leader, a global leader, in R&D efforts for decades.

And we continue to fund the majority of annual global R&D efforts. In fact, in 2018, the United States spent about \$580 billion on R&D, more than any other in the Organization for Economic Cooperation and Development, including China. Two sectors, businesses and the federal government, have, together, accounted for more than 90 percent of U.S. R&D funding since 1953.

And as we recognize the importance of federal investments in R&D, Congress must do more to remove any barriers that may discourage the private sector from taking the lead on product development.

And this, you know, COVID-19 pandemic has exposed our nation's reliance on other countries to supply the production of critical supplies like PPE and other things, and it has highlighted the importance of creating products, supply chains, and intellectual capital right here at home.

It is time to fully unleash Americans' spirit of innovation, which is why I recently introduced the Advancing Tech Startups Act to promote a national strategy for encouraging more tech-focused startups and small businesses in all parts of the United States, not just out west in Silicon Valley. This legislation would direct the Commerce Department to identify any federal rules or regulations acting as barriers to creation, development, and growth of technology startup companies.

You know, America's innovation base starts with R&D, and Congress should continue supporting federal investments in basic research and early stage applied research while simultaneously re-

moving any barriers that may hinder the private sector's role in product development.

So, Dr. Shih, according to the Congressional Budget Office, the private sector has been the primary source of funds for R&D in the United States since 1980. Given that the private sector has taken over a growing number of our nation's R&D needs over time, what is the proper role of the federal government, in your view, in research and development?

Dr. SHIH. I think the proper role of the federal government is to fund risky, frontier research which is beyond the capabilities of private firms to necessarily recognize a return. OK? And, historically, that is why you think of that kind of basic science, basic research as a public good, right?

And the country has done this. We have done this in terms of audacious bets. I point to DARPA as a great example of funding audacious bets. You know, today, we see the private sector investing a lot in autonomous driving. Well, that was because DARPA did the proof of concept, the risky first steps, back in the early 2000's, 10 years before it really became as popular as it is now.

So I see the role of the federal government is really that frontier, risky stuff where you don't have the guaranteed results.

Mr. JOHNSON. OK.

Well, let's flip the coin in the other direction then. In your opinion, are there any federal barriers that have hindered or could hinder future R&D efforts? In other words, are there places where it would be better if the federal government stepped aside rather than getting into the mix?

Dr. SHIH. Well, you know, I think, you know, for me—and a number of other speakers have talked about this—the importance of developing capabilities in people, OK, and that talent pipeline, right? We see the federal government now really impacting that talent pipeline.

I am a student of history, and I go back to, you know, in the 1910's, if you wanted a graduate education, you had to go to Germany, OK? Even the early 1920's, if you wanted a graduate education, you would complete your work at one of the great land-grant—I am a great fan of the Morrill Act and the land-grant colleges. OK. But if you wanted a graduate education, you went to Germany.

OK. But what happened in the 1930's? The government there destroyed what they had. OK. And we had the presence of mind to go scoop up a lot of those people, right?

So that would be one area where I have a lot of concerns, actually, because talent is what this is all about.

Mr. JOHNSON. OK. Well, thanks.

We could talk about this all day. I have got a lot of additional thoughts, but my time has expired.

Mr. Chairman, I yield back.

Chairman YARMUTH. Thanks.

The gentleman's time has expired.

I now recognize the gentlewoman from Illinois, Ms. Schakowsky, for five minutes.

Ms. SCHAKOWSKY. Thank you very much, Mr. Chairman.

I first just want to associate myself with the remarks of David Price, talking about—I have universities in my district. I have a very diverse district. And the fact that these students, who are here contributing to the kind of R&D that we need, are in danger now of having to leave our country, I think it will be a tremendous loss to innovation if they are expelled. I hope we change that.

I am absolutely a firm believer in the importance of federal investment into research and development. Alongside almost all of my colleagues, we voted for three COVID-19 relief packages in March that provided approximately \$7.5 billion for the “development of necessary countermeasures and vaccines.”

So we have put in a lot of money. And I wanted to make the point of who put the money in. Taxpayers have invested heavily in research and development in this fight against COVID-19. And yet, despite this substantial investment of billions of taxpayer dollars into COVID-19 vaccines, still we do not have any commitment that they will be affordable and accessible and available to all who need them.

And we are already seeing that there is that kind of divide, the kind of price-gouging, I would say, when we have Gilead, who produces Remdesivir, which is not even a cure—it helps alleviate some of the symptoms—charging per system of—it is, like, five, I don’t know, it is five parts of a treatment—\$3,100-plus per treatment. Now, who is going to be able to afford that? It is just, I think, unconscionable.

And then we saw the government give \$1.6 billion to a company who has never actually—Novavax—produced a drug, and they now have the ability to get \$1.6 billion.

So my view of this COVID issue is that, if we don’t make this available to everyone, it is like making it available to no one. Because if it is not available here in this country and to the rest of the world, we are all at risk of continuing, forever, this virus. We have to make it absolutely accessible.

And I have introduced legislation called the MAP Act, H.R. 7296, that would actually fix that, along with Representatives Doggett and DeLauro and DeFazio and Rooney—bipartisan. And that bill would prevent price-gouging. It would prohibit monopolies. It would ensure transparency on taxpayer-funded drugs.

So I want to ask Dr. Parikh, given the necessity of us finding a cure somewhere in the world, I want to ask you, do you believe that we can and should ensure that the benefits of the Federal R&D, like lifesaving drugs, aren’t priced out of reach?

Dr. PARIKH. Thank you for the question.

I will start by saying I am a biochemist, not an economist. But at the AAAS, the American Association for the Advancement of Science, part of our mission is to advance science and serve society. And so the scalability and accessibility of developments in science is certainly important to us, and we would want to see the public health of the nation, of all people, benefit from our research investment.

Ms. SCHAKOWSKY. And isn’t there some danger, if everybody doesn’t have it accessible, that we could all be still susceptible to the virus?

Dr. PARIKH. You certainly would like a vaccine to be as broadly available as possible.

Ms. SCHAKOWSKY. I have two seconds, one second, I am out of time, and I yield back.

Chairman YARMUTH. The gentlewoman yields back.

I now recognize the gentleman from Texas, Mr. Flores, for five minutes.

Mr. Flores?

Is he here?

Make sure you are unmuted, Mr. Flores, if you are still on.

Well, in that case, if he is on, we will come back to him, and I will yield five minutes to the gentleman from Tennessee, Mr. Burchett.

Mr. BURCHETT. All right. Can you hear me, Mr. Chairman?

Chairman YARMUTH. I hear you, sir.

Mr. BURCHETT. Right on. Thank you, brother. Thank you for allowing me to be here.

Is he back on?

Chairman YARMUTH. Mr. Flores, are you on?

Well, we will come back and get him if he is. Go ahead, Mr. Burchett.

Mr. BURCHETT. If we need to, that is cool, Mr. Chairman. I understand. I am the 435th most powerful person in Congress, so I understand my role as a freshman. Thank you, brother.

Everybody knows east Tennessee is home to Oak Ridge National Laboratory, and it is the largest of the Department of Energy's 17 national laboratories. Over 2,900 ORNL employees reside in my district that I represent. Of course, they contribute very much to the rich tapestry of our area.

And I am concerned, I guess, more than anything else—and maybe Dr. Parikh or Ms. Wince-Smith could answer this. Has the overall federal response to COVID-19 adequately employed the expertise and tools we have at our national laboratories?

Dr. PARIKH. Thank you for the question—

Ms. WINCE-SMITH. on that—

Dr. PARIKH. Oh, go ahead, Deborah.

Ms. WINCE-SMITH. I will jump on that, because—first of all, thank you for everything you do to support Oak Ridge National Laboratory and the whole ecosystem of universities and companies that are there. It really is one of our national treasures.

I had the opportunity to be there for the dedication of the carbon composite manufacturing facility that is very, very important in our manufacturing infrastructure.

I do think that one area where the national labs are playing a huge role—and let's not forget that the whole research that led to the Human Genome Project came out of work at Los Alamos years ago.

But one area where they are really leading the way is bringing together their huge, state-of-the-art, world-class assets in high-performance computing, exoscale computing, artificial intelligence, in both, you know, working with the private sector in a new consortium to both understand mitigation, transmutation, all the things that are happening to the virus itself using these computational capabilities.

And also, of course, linking that to their tremendous capabilities in materials research. And another lab that is very much involved in this in the biopharmaceutical space is Argonne National Lab.

So these laboratories have these very powerful user facilities that universities and companies can come and use. And no one, quite frankly, in the world has them on the scale that we do.

Mr. BURCHETT. But are we utilizing—I appreciate all that. I don't want to run out of time, and I want Dr. Parikh to be able to answer that. Do you think we are utilizing that, though?

Ms. WINCE-SMITH. I think we can use them more.

Mr. BURCHETT. OK. OK. I agree with you, ma'am.

And I appreciate Oak Ridge National Laboratory. If you go there, you really should go by Big Ed's Pizza. I just want to leave it at that. Make sure you go there.

Doc, thank you so much. We have a huge Indian community here in Knoxville, in my area, and they are great folks. The longest withstanding democracy in the world, and they make Enfield motorcycles, so I am a big fan of India. And a lot of their folks—you know, we laugh about it, but I have a big time when they have the IndiaFest.

But go ahead. I wanted to hear what you had to say too, brother.

Dr. PARIKH. Yes.

Look, Oak Ridge National Lab is a national treasure. We could be doing more. Even the materials science work going on, in terms of making PPE in slightly different ways and making it more quickly, is just fantastic work.

What it speaks to, though, is that the sciences, they all cross-pollinate. Just because you are working in physics or you are working in materials science doesn't mean that you are not involved in healthcare and vice versa and the computing as well.

So this really speaks to the fact that, you know, this linear model of Vannevar Bush, it is outdated, because all these things mesh together. And they mesh together in a coordinated way, like with COVID, where we have basically looked at this entire virus over the course of three months and know everything about it at the atomic level.

All that has changed over the last 20 years, and we have to update how we use the national labs and how we use basic research.

Mr. BURCHETT. Well, what barriers do you all think that we could eliminate at our laboratories so we can better get to the answers?

Ms. WINCE-SMITH.

[Inaudible.]

Dr. PARIKH. I think you are on mute, Deborah.

Ms. WINCE-SMITH. I was trying to say, the mission really needs to include economic competitiveness and enhanced collaboration with industry, in addition to the core national-security and energy missions.

Dr. PARIKH. And, just quickly, getting intellectual property out of the laboratories should be as easy as possible, particularly for things that aren't related to security and national defense.

Mr. BURCHETT. OK. Thank you all so much.

Thank you, Mr. Chairman. And I see that I woke up Dan Crenshaw, and I will anxiously wait for his rebuttal to everything I

have said today. But thanks. I really miss seeing you guys in real life. I wish this thing would get over before too long. But I really dig our relationship and our friendship, so thank you all.

Chairman YARMUTH. I think we all do that. I thank the gentleman.

His time has expired.

I now recognize the gentleman from Michigan, Mr. Kildee, for five minutes.

Mr. KILDEE. Well, thank you, Mr. Chairman, for holding this really important hearing.

It comes at an important time. Obviously, we are in a pretty unprecedented moment right now. And it does give us an opportunity and I think the necessity to think through the basic elements of our economy and what the future is going to look like. We have the time and I think the real necessity to think that through.

In Michigan, you know, we are the center of the automotive industry. I am from Flint, which is the birthplace of General Motors. I might have mentioned that I am from Flint a time or two.

But the auto industry is in a transitional phase. And, in fact, there is a movement toward electrification. The market is heading in that direction. And we will benefit from that. We will benefit in terms of the environmental impact of autos, but we will also benefit in terms of safety and ultimately in terms of savings for consumers.

Right now, China is the number-one manufacturer of electric vehicles in the world, so we have to do more, I believe, to get in front of our competition.

I am a hockey player. I like to go where the puck is going, not chasing it all the time. And I think the market is taking us there. And we need to think about the incentives that we need to put in place in order to win the future when it comes to vehicles, particularly around electric vehicles.

My act, the Driving America Forward Act, would expand the electric vehicle tax credit. That is one way to incentivize investment in electric vehicles, and I think it is an important way on the demand side to create some incentives. But it is not all we need to do. The movement toward this technology will require significant new research and development.

And I am particularly concerned that some of the auto manufacturers, the OEMs, are burning a lot of their cash that normally would be devoted to R&D right now just to maintain operations. They are burning their reserves. That is a problem.

But I am wondering, perhaps, Ms. Wince-Smith, if you might comment on how we can continue to make the investments, given the fact, as you reference, that China is significantly ramping up, catching us, will pass us, in terms of their investment in R&D.

How can we continue to lean in, be competitive, invest, given the fact that we respect openness, we respect and embrace collaboration and the synergy that comes from that, given the fact that China engages in all of these practices that we know are destructive and actually, you know, counter-competitive, you know, their acquisition of trade secrets, all the things that they do?

We live in a world of openness. We live in a world where we like to see that synergy. Can you talk a little bit about how we can con-

tinue to advance ourselves in terms of the R&D we do in this space, given the fact that, culturally, we have a different approach?

Ms. WINCE-SMITH. One thing I think we need to consider in this new game plan for the future is to look at some of the legislation that was very timely when it was passed but it needs updating.

So one, of course, is the research and development tax credits, but also the Cooperative Research and Development Act, which gave some limited relief from collaboration with fear of treble damages and antitrust. And we really need to have more clarity on how, for instance, the U.S. automakers could come together without fear of antitrust actions coming to them to work collaboratively and pool their resources around the next-generation advanced battery technology. Because that is really a holy grail for all of this.

So that is one thing that I would highly recommend, but also, you know, looking at the tax credit on the research and development. But instead of everybody competing on the battery side—and there is the Advanced Battery Consortium that Argonne Lab and the universities participate in, and some of the companies, but I think that needs to be accelerated in a big way.

The second thing is really the state regulations and certainly the energy regulatory commissions state-by-state that set a patchwork of regulation, and the extent to which there could be some national imperative to look at the electrification as a national goal and need, back to Dr. Shih's comments about demand. Because, right now, we have a patchwork of state-by-state regulation that acts as a barrier.

One thing that is an example from COVID is that we were able to bust through a lot of the regulatory impediments that have inhibited telemedicine. You know, state-by-state was regulating it, and there was preemption because of the need to have telemedicine.

So I think there is a lot could be done on the tax, fiscal, regulatory environment, but to enable the pooling together of assets among these companies. And another area would be in the critical materials, too, that they need.

Mr. KILDEE. Thank you.

My time has expired. I really appreciate the testimony of the witnesses.

Mr. Chairman, I yield back.

Chairman YARMUTH. The gentleman's time has expired.

I now recognize the gentleman from Texas, Mr. Crenshaw, for five minutes.

Mr. CRENSHAW. Thank you, Mr. Chairman. Thank you for holding this hearing.

America really is the greatest nation in the world, best equipped to answer the world's challenges. We have the finest institutions, the brightest thinkers, and the structure of our country is set up so private citizens are able to change the world with their innovations.

In fact, it is in one of our duties in the Constitution, Article I, Section 8, Clause 8 of the Constitution, "to promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and

discoveries.” Such an important line. Patent protection, personal property rights, the ability to sell your invention.

And it is because of these protections of personal property rights and private property and our willingness to invest in the big problems and a governing system that allows the testing and marketing of new products that have brought millions of people out of poverty and allowed for higher standards of living, not just in the U.S. but around those globe.

A lot of those innovators are here in Houston, solving problems of zero-emissions electricity through natural gas at NET Power, which I have talked about a lot; curing childhood cancer at the Texas Medical Center; and, of course, our very own Rice University, which is really a standalone powerhouse in innovation.

I think we can all agree, American dominance in finding a cure for coronavirus is important. And the fact that we are dominating that search reminds us that we still are No. 1. We have 321 companies researching a novel vaccine or treatment for the virus. This is in contrast to the next-closest country, China, which has only 39. The whole of Europe has just under 100.

This hearing is important because we should be looking forward at the next set of challenges, and we should be working—as we work toward this. And I know there is a narrative out there that we are falling very far behind, but the U.N. has us ranked No. 3 in the Innovation Index, behind Switzerland and Sweden.

The same report by the U.N. highlights something really important: that we need to push resources and global R&D toward biomedical innovation. Alzheimer’s, ALS, cancer, diabetes—all of these are listed as crucial needs for innovation, according to this Innovation Index by the U.N.

Well, let’s remember, it is not just R&D spending that matters. That doesn’t mean you are going to create the next big thing. There also has to be a free market, demand for it, and patent protection. Otherwise, we never get that next cure.

Take, for example, Taiwan. It has very high R&D investment, No. 8 in the world actually, but their biotech market is extremely small. They produce very few new drugs, if any. Why? Price controls. So it is not a surprise that no one will take on risky investments if there is no payoff. Why would any life sciences company want to operate in Taiwan and sell to Taiwan when they have to deal with burdensome price-control regulations?

OK. So my first question for Dr. Shih.

With that in mind, what would be the impact on American medical innovation if we reverted to a Taiwanese model of drug pricing?

Dr. SHIH. Well, Taiwan has been more successful in, you know, other sectors than bio-med. I have looked at some of the bio-med things. I think the ability to recoup a return on investment to fund further R&D is important, right, and that is why patent protection is very important.

Now, when we talk about the pandemic, OK, we also have instances, for example, where you really have a global health problem, right, which I think was pointed out earlier, right. And those call for maybe—you know, you almost have a market failure, because the companies aren’t incented to work on low-cost vaccines,

for example, for poor regions, where, in fact, the poor regions, if you don't get the infection under control there, it is going to come back to us.

But I do believe it is important to provide incentives. And, by the way, part of the patent bargain which is disclosed in the Constitution is, it only gives it to you for a limited period of time, right, which is, in exchange for making that R&D investment, then, you know, you get to reap the returns for some period. So I think it is important.

Mr. CRENSHAW. Absolutely. And we don't want to lose that. And I think that is the point of maintaining American innovation. Because if we weren't a biomedical powerhouse, what country do you think would be next in line to provide the world with that next ALS cure, the next Alzheimer's cure, et cetera?

Dr. SHIH. It would probably be the Europeans, right, who are investing very heavily in Germany, in Denmark, you know, in—for example, I went to one company in Denmark that provides 70 percent of the world's allergy immunotherapies, OK, and I visited the factory there that provides 50 percent of the world's insulin, OK.

And so the Europeans are taking these long-term views. They are also, to the point that was raised earlier, funding collaborative, precompetitive research in many areas. You see this in batteries most recently, OK, and you see it in electrification and things like that.

Mr. CRENSHAW. Well, I am out of time. That went fast. Thank you.

Chairman YARMUTH. The gentleman's time has expired.

I now recognize the gentleman from California, Mr. Panetta, for five minutes.

Mr. PANETTA. Thank you, Mr. Chairman.

And thank you, Ranking Member Womack. Good to hear about the investment at the University of Arkansas, not just in the new football coach but in the research that is going on there. Pig Soobie.

Let me also just comment, if I can, and echo the sentiments by Dr. Parikh and Professor Price, Congressman Price, in regards to the new policy that has been put out about removing visas for students who are legally here, studying at colleges that have chosen to go remote-only.

Basically, making that decision to protect the health and safety of their students unfortunately has led to a senseless decision by this Administration to remove those students that contribute so much not just to our educational systems but ultimately to our economy and to the research and diversity of this great nation. So I appreciate those comments.

And that is exactly why I am leading a letter to the Honorable Chad Wolf, Acting Secretary of the Department of Homeland Security, asking Secretary Wolf to revisit this decision and hopefully answer some significant questions as to why they would implement, or try to implement, such a divisive policy, especially now during this pandemic. So I hope other Members take a look at that letter and sign on, if interested.

Obviously, being from the central coast of California, immigration is very important to us for a number of reasons. It contributes

to our economy, our communities, and ultimately our culture. I wholeheartedly believe in that.

As my good friend Dan Kildee knows well, I come from the “salad bowl of the world,” so we have a lot of agriculture here. We have a lot of specialty crops here. And we also know that, in order to sustain those types of crops, the most important thing—immigration is a big issue, but it is also research into those types of crops.

And we are lucky to have the universities that we do here, that do invest in that type of research. We also have a USDA agricultural research station that makes those sort of investments. But, ultimately, what it comes down to is, we need more federal funding for that.

Now, I think, historically, the United States has been on the forefront of agricultural research and innovation, but we are being outspent by our competitors. And now we are seeing a 40-percent return on investment. Despite that, the U.S. public-sector funding for agriculture research is declining. And, obviously, I am concerned about those types of implications, those types of trends, when it comes to our food security as well as our food sustainability.

Now, in Congress, I am trying to do my part in more ways than one, than to just talk about the “salad bowl of the world,” but making sure that we actually get other Members involved. And Rodney Davis, a Republican, and myself have started the Ag Research Caucus to highlight the importance of federal investments in agriculture research.

But if I can direct a couple questions to Dr. Parikh and Dr. Romer.

Can you comment on the decline in U.S. investments in Ag research and the potential implications of this trend in both our domestic and global food security, as well as any sort of solutions, especially when it comes to partnering with private companies as well?

Dr. PARIKH. Thank you.

Yes, you know, the decrease over time is probably a result of the success of the programs. The U.S. has become the—you know, it is the bread basket of the world, and our farmers have done a wonderful job of feeding the world. And a lot of that has come because of the work of the ARS and the USDA in transmitting the best information about how to make yields better, how to make crops better, and how to supply a product that the market wants.

In terms of—you know, I actually think this is a perfect example of what Dr. Romer talked about—so I will stop talking and let him talk, because he is the expert in this—of this move to, you know, useful, useful research at a grand scale locally.

Dr. Romer?

Dr. ROMER. Yes. Agriculture research was one of the real successes in the pre-World War II systems in the United States. And it was research that was spread throughout the country that was focused on practical benefits. It is very important to the future of the world, because we have to keep raising productivity to keep up with growing population and growing demand for meat.

And it is the kind of thing which, frankly, has been squeezed out because professors in the top universities want to work on the cut-

ting-edge issues, like genomics, which was very important basic science, but the bread and butter of agricultural research is being neglected.

And so, when I called for a return to what worked before World War II, it is not to take away from the new things in basic research we do, but to go back to supporting those things.

Let me just say, there are also potential funding mechanisms that could guarantee this. The commodity producers can levy a tax on themselves to, for example, pay for ads. If you remember the dancing raisins and so forth. I think we should be looking for ways for agricultural groups to tax themselves so that they are the ones who are actually allocating the research dollars.

And they can use those dollars both to get practical research done in universities throughout the country but also to encourage students to get trained in the kinds of skills and habits of mind that will lead to productivity increase in agriculture.

Mr. PANETTA. Great. Thank you for those answers.

I am out of time. I yield back. Thank you, Mr. Chairman, again.

Chairman YARMUTH. Absolutely.

The gentleman's time has expired.

I now recognize the gentleman from Texas, Mr. Flores, for five minutes.

Unmute your mic.

Mr. FLORES. That is two times today I have done that. Sorry about that.

I appreciate the testimony that we have had today, and I appreciate the value of the hearing.

I have always referred to basic research as the seed corn for future economic growth and human opportunity. And, in this regard, I appreciated Dr. Shih's opening comments, where he said that government support of basic and applied research can fertilize the soil, but it takes private companies willing to make a long-term investment in risky R&D to build that, and that the role of the federal government should be to enable and support, not hinder, the private sector to lead the way in restoring U.S. manufacturing capabilities and competitiveness.

I represent two of the largest Tier 1 public research universities in the country. One of them, my alma mater, is the largest land-grant university in the United States, and it educates nearly 70,000 students annually, preparing them for cutting-edge jobs in Texas, the U.S., and, actually, all over the world. And with almost \$340 million in annual research expenditures, Texas A&M University provides solutions to challenging national problems ranging from hypersonics to vaccine development to vaccine manufacturing. And this research serves as a cornerstone to the regional economy, and it is critical to the future economic growth of this country.

Like many sectors of the economy, research universities like Texas A&M have been hit hard by the impacts of COVID-19. And, during the past few weeks, only essential research has continued on campus, and, as a result of that, the university has experienced over \$30 million in research losses. And worse than that, the cumulative impact of the delayed research is going to have a huge economic impact for the country. And so those numbers continue to grow.

So, given the importance of research for our present and future competitiveness, I support the bipartisan RISE Act, which includes additional resources to help offset those losses that are being experienced by the research institutions. I would urge my colleagues to support the inclusion of these RISE Act provisions in the next relief package.

Ms. Wince-Smith, a couple of questions for you, if you don't mind.

The first one is, during the COVID-19 pandemic, what do you think are the most effective ways to assist universities with their vital research efforts? Do you think funding research shortfalls created by lab shutdowns, like we envision in the RISE Act, is a wise public investment?

Ms. WINCE-SMITH. Thank you, Congressman. Well, first of all, congratulations on the leadership and contribution of Texas A&M University. They are a very active member of the Council on Competitiveness. Tremendous engineering and ag capability. They really are a star in our firmament of universities in the United States.

I do think the RISE Act really is very important at this time, because if we allow the atrophying of a lot of these ongoing research activities, we will potentially lose the people. It is back to the people issue.

And, of course, it also links to the immigration challenge that we are facing right now that others have mentioned, in terms of ensuring the continuity of research. Because the speed and scope of what we need to do across the board really cannot be interrupted without damaging, you know, that infrastructure.

So the RISE Act, I think, is a very important initiative for Congress to consider in the next phase of COVID relief.

Having said that, I do think we are seeing tremendous innovation now coming out of universities in looking at their business models. And many universities are really still structured sort of on a 19th-century model, and we have seen others that have moved very quickly to embrace lots of innovations in how they are delivering education, involving young people and designing programs and things.

Mr. FLORES. Yes.

Ms. WINCE-SMITH. So I would project that in the years ahead our university system is going to look very different than it does right now.

Mr. FLORES. Yes.

Ms. WINCE-SMITH. Having said that, we can't disrupt our research, and we need to make sure we have the talented people to keep that going.

Mr. FLORES. OK. If I can get one more—

Dr. ROMER. If I could just weigh in here, there is a very important issue here. The way to get research going again in universities is to do what Stanford Medical Center did, which was test every person in the medical center who is patient-facing and to test patients as they come back in. So they have reopened Stanford Medical Center, and it is operating just the way it did before.

We could do this in every university if we used the testing resources that universities have available to them to test everybody, and test everybody frequently, but to get back to the work on uni-

versity campuses. And the bottleneck here is the CDC and the FDA, who are impeding our ability to do this kind of testing.

Mr. FLORES. OK. Thank you.

Chairman Yarmuth, I have one more question, but you will probably shut me down, so I will submit it for the record.

Chairman YARMUTH. No, go ahead. Since Dr. Romer wanted to add to that. Go right ahead.

Mr. FLORES. OK. Thank you for your forbearance.

This question is also for Ms. Wince-Smith.

You know, you brought up the people resources, which are, of course, our most important resource. As the pandemic continues, universities like A&M have made a commitment to continue paying those researchers, including graduate students and principal investigators. And I applaud the effort that the universities are making to ensure that our research work force pipeline continues.

How can the federal government support the training and education of this future work force during this challenging time?

Ms. WINCE-SMITH. A very, very important question. I would like to expand it, if I may, a little bit to look at parts of the country where we have, you know, tremendous unemployment, we have tremendous hardship underway, including lots of social issues. And the extent to which the universities can link—the big research universities—with community colleges and some of the other work force boards to train and pool their resources to ensure that we can continue the upskilling of our work force.

I know there are controversial issues around the H-1B visas and, you know, the numbers of these and how this impacts U.S. jobs, et cetera. But, at the same time—and I think my colleagues have said this as well—we need to have a balance between attracting, keeping, retaining the best and brightest around the world in this research enterprise but double down on educating and training our own citizens, particularly women, minorities, underrepresented racial groups. And that is part of the equity of our democracy. And this is an opportunity to really focus on that right now.

Mr. FLORES. I agree.

Thank you, Mr. Chairman, for the forbearance.

And, Jimmy Panetta, I would like to join your Ag Research Caucus, if that is OK.

I yield back.

Chairman YARMUTH. The gentleman's time has expired.

I now recognize the gentleman from New York, Mr. Morelle, for five minutes.

Mr. MORELLE. Good afternoon. Thank you first, Mr. Chairman, for holding this what I think is a critically important hearing.

And when I was—I just finished 26, 28 years in the state legislature in New York representing Rochester, New York, which, you know, we spent a lot of time on innovation and technology as a way to revitalize our old, industrial cities.

And I know, Dr. Romer, we miss you at the University of Rochester. I know you spent part of your career there, so we claim you as part of our own, but you know well the challenge that we face.

In fact, I was just looking at—I have been reading "Jump-Starting America," which you may be familiar with, all the panelists, written by John Gruber and Simon Johnson, who I had a chance

to spend some time with both on the phone and at dinner recently. It actually talks about innovation as federal investment and why it is important. It also just happens to rank Rochester, New York, as No. 1 in the country if we make major investments. So we are very proud of that.

But all of this is really premised on the notion that more than 85 percent, I believe, of our nation's economic growth since World War II—so we are now approaching, you know, 75 years where all of our success, or a substantial part of our success, has been attributed to scientific/technological research, innovation, and progress. It is alarming to me when we talk about reducing that investment and reducing federal investment in those activities.

I just want to—since I bragged on about Rochester, I am going to brag a little more, if I can, and just use this as a case in point. Our district is lucky. At the University of Rochester's Medical Center, we are part of the New York Influenza Center of Excellence, one of the five international centers in the centers of excellence in influenza research and surveillance network. And we are one of only nine of the National Institutes of Health vaccine and treatment evaluation units—particularly appropriate given where we are with the pandemic.

But this has been made possible for the past five years because the U of R has attracted more than \$1.93 billion in sponsored research funding to the region and is a national leader in translating discoveries into new technology. We have a brand-new clinical translational sciences cluster that we have created.

We are doing this around technologies, applications, companies that treat and cure disease, improve national security, help our nation move toward sustainable, clean energy.

If we as a Congress continue to invest in federal research, institutions across our country, just like the University of Rochester, probably like Texas A&M, and all of the amazing universities we have in the United States, we can do so much more to harness innovation and discoveries into commercially viable technologies and companies.

So I am proud to say that many of our U of R scientists are working right now on conducting clinical trials of vaccines, treatments, and diagnostics for COVID-19.

But I do want to—and I apologize for the long intro, but I did want to ask Dr. Romer, what specific policies or general thoughts do you have about approaches that we should consider to help ensure that the immense scientific understanding and capacity of the United States is actually transitioned into use into the broader economy and into society at large? How do we make that transition? What should we be doing as a Congress and as a country to help that transition?

Dr. ROMER. I think there are two things.

One is invest in people and then try and be the place where people want to stay and work. That means we can keep attracting well-trained people from the rest of the world, but we are really underinvesting in our own U.S. talent. And this is why I think fellowship programs and an attempt to redo what we did with, like, electrical engineering, chemical engineering could be so important

now. So invest in people, and use all of our universities to carry out that mission.

The second is, you know, I talked about having agricultural producers influence what happens on university campuses. I think in Rochester you see a good example of this in optics, where Kodak and then Bausch & Lomb encouraged work on particular questions and then encouraged training of students on questions related to optics, which turned out to be very important for lasers and a number of other kinds of applications.

Mr. MORELLE. I couldn't agree more.

I will say this, that we in the state and the federal government have both created a big optics and imaging manufacturing institute. The United States invested; the state of New York has invested. I think we invested \$250 million on optics and photonics, exactly what you are saying, to make that investment in photonics. You know, photons move faster than electrons.

Dr. ROMER. Yes. And I guess the way to say what I am saying is that professors are a huge asset, a huge resource, but we need some other voices that are contributing to the decisions about where universities go. And if we gave fellowships, we could empower students to have a little bit more say. And if we put industry groups in a position to spend their own money on either research or training, that would bring their voices to the table too.

Mr. MORELLE. Very good. Thank you, Doctor.

Thank you, Mr. Chairman, for another great hearing. Appreciate it.

Chairman YARMUTH. The gentleman's time has expired.

I now recognize the gentleman from Virginia, Mr. Scott, for five minutes.

Mr. SCOTT. Thank you. Thank you, Mr. Chairman. This has been a very interesting hearing.

I want to thank our witnesses for being with us today.

I would like to ask a question to Dr. Parikh.

You mentioned the value in getting and a need for data in order to make informed decisions in the criminal justice area. The Death in Custody Reporting Act requires the Department of Justice to collect data on deaths that occur in jails, prisons, and in the process of arrest, but the Administration has not followed the law and hasn't collected the data.

If they had followed the law or would begin to follow the law, the information that would be collected would be demographic information and a brief narrative of what happened. If you collected that on deaths in custody all over the country, how could you use that data to make informed decisions in the criminal justice area?

Dr. PARIKH. Thank you for the question, Mr. Scott.

You know, it is challenging. We have social scientists who are very interested in looking at this data, analyzing this data, and providing prescriptions. Sometimes you don't know what those prescriptions are going to be until you have seen the data and are able to analyze it. So I don't want to—I wouldn't want to presuppose. And I am a biochemist, so I want to represent my social scientists well.

But what I will say is that they feel very strongly that, with access to data, they can provide prescriptions for national policy, at

least inform policy. And transparency leads to that ability to analyze the data.

And so they would argue very strongly that we need to have transparency of demographics, of data related to violence, of data related to incarceration. These are all points of question that my social scientist stakeholders within the AAAS would say are very important and, frankly, could do a great deal toward working to make the world a fairer place.

Mr. SCOTT. Thank you.

I have one other question I just would pose to all of the witnesses. Dr. Shih had mentioned that the basic research is done by government, and then when you get to proof of concept, the corporations come and do the—when profit is around the corner, they can be counted on doing the rest of the research.

The way we fund research is a number of different ways: R&D tax credits, where the corporations get to decide what they want to do; direct cash, if you have something you want to research; or direct investments in NASA, Energy labs, NIH, and things like that.

How could you get better coordination—wouldn't you get better coordination with the investments in NASA, NIH, and the Energy labs and wouldn't it be better coordination and more bang for the buck if that is where you put your federal dollars on research, rather than let corporations go wherever they want to go and they probably would have done it anyway?

Dr. SHIH. Well, let me suggest something. I think it is a very interesting question. I think we are actually at the threshold of an opportunity, OK, because I think it has historically been the federal government's role to fund basic R&D, but the government can also, especially in this pandemic recovery phase, when we are going to spending a lot on infrastructure, I think we can also create demand, right? So there will be push on the supply and pull from the demand, which would cause people to invest in particular areas, right?

So, I mean, we are seeing a microcosm of that right now with vaccines and therapies for COVID-19. OK. But I think there are other areas, for example, where, if we want to spend on infrastructure—I am a big fan of grid modernization, right? Especially if you are from California, you know how obsolete our grid is, how vulnerable it is to disruption. OK.

But if there were investments, infrastructure investments, on grid modernization, it would drive a whole bunch of R&D, for example, in silicon-carbide power devices, right, energy storage technologies, group III-V semiconductors, and a whole bunch of other areas, right?

So I think taking a more holistic and, I would say, strategic view on that, we really have an opportunity coming out of this crisis to do that.

Mr. SCOTT. Can I get Dr. Romer to comment very briefly on that question?

Dr. ROMER. I think it is important to remember that we get huge benefits from a decentralized system that can focus on different issues.

For example, at the University of Minnesota, they developed a technology for pelletizing iron ore which was crucial for exploiting its iron ore reserves, and it has turned out to be very important in many other areas. A nationally controlled, centralized system might not have focused on pelletization, but the local forces in Minnesota encouraged that kind of research.

So I think——

Mr. SCOTT. That was federal funding, I would imagine, federal or state funding, not corporate——

Dr. ROMER. Well, no, it was really the federal government's support for the land-grant institutions. So the federal government provided the background resources, but the actual decisions about the spending and the research to pursue were made locally.

So I think we should be open to a system that allows a lot more decentralized decisionmaking on the specific research projects that are pursued.

Mr. SCOTT. Thank you, Mr. Chairman. The point I was making, if you spend a lot of money on R&D, the corporations get to do it. If you do things like fund the research at universities, fund NASA, fund Energy labs, fund NIH, it gets decentralized, but I think you get a much better bang for your buck. By the time the corporations get around, the basic research is done, profits are around the corner, and they probably would have done most of that anyway.

So thank you. I appreciate your indulgence.

Chairman YARMUTH. You have a man with the gavel on the Committee. No problem.

The gentleman's time has expired.

I now recognize the gentlewoman from Texas, Ms. Jackson Lee, for five minutes.

Ms. JACKSON LEE. Thank you very much, Mr. Chairman. Can I be heard?

Chairman YARMUTH. Yes.

Ms. JACKSON LEE. Thank you very much.

Thank you to all the witnesses as well.

I am glad to join this Budget Committee that is focusing on the necessity of research so we can save lives.

Let me read into the record, first of all, the number of confirmed cases of COVID-19 in the United States, which is now a little bit over 3 million cases. Confirmed cases in Harris County, 39,311; deaths, 395; confirmed cases in Houston, 55,122; deaths at 581.

Those numbers have gone up from the moment that the state decided, as of May 1, to end the stay-at-home order and, of course, to begin to open up the state.

Business and the economy are very important, but it is extremely important to remember that R&D is a preventative measure that provides the opportunity to be prepared. And one of the issues in fighting COVID-19 is a question of preparation.

So I would like to ask Dr. Parikh, specifically, R&D as it relates to where we are today. The idea of working with huge pharmaceuticals, which obviously exist—AstraZeneca received \$1 billion to engage in vaccine research. A small company like Greffex, G-r-e-f-f-e-x, Incorporated, in some of the clinical trials that are going on here in Houston have had to struggle to get the attention of the federal government.

What would have been the results of a proactive research R&D protocol for the United States where we would engage with research dealing with infectious diseases or the potential of diseases that, really, we have seen around the world?

Dr. Parikh?

Dr. PARIKH. Thank you.

I think what we are seeing is sort of a reflection of the investments that we have made over time. We have made a lot of investment in the basic research and in biomedical research. And so, when the virus was isolated, the fact that within three months we had characterized the atomic structure of the coat protein and we had all of the necessary information for starting vaccine trials is amazing. It is absolutely breathtaking. And that is the result of all the research and investment that has been made over the last 20 years in that infrastructure.

But then you also see the lack of investment in public health. You see the atrophy that has taken place in our public health departments around the country. You see some of the atrophy that has taken place at CDC. And so what you didn't get was the immediate public health response and the powerful public health response that could have helped us in the initial stages of the pandemic.

You know, I think we should be very careful in terms of how we are guiding the science. There is this research project that was looking at bat coronaviruses that had some fieldwork in China, but that work was canceled by the Administration.

And, you know, one of the things that I really worry about is scientific integrity. There are lots of reasons, and administrations are within their rights to cancel research projects. But they shouldn't make the scientists the instrument of that cancellation—

Ms. JACKSON LEE. Thank you. Thank you very much.

Dr. PARIKH. Thank you.

Ms. JACKSON LEE. Thank you very much. My time is short.

Let me proceed—and thank you very much for your answer—to Deborah Wince-Smith, the Honorable Deborah Wince-Smith, on my specific point about the value of competitiveness in the United States and the importance of building a body politic of small researchers to be able to engage in competitiveness.

And, as I indicated, there are clinical trials going on here in Houston, Texas, dealing with COVID-19 that are not able to pierce the structure in the federal government, and, therefore, their research is languishing.

I think the comments of Dr. Parikh were important about the infrastructure of health, public health, but it also is important that we do follow the science but that we also have the R&D structure, the funding for R&D, that we promote all of this research that is going on in the United States that may not be the size of AstraZeneca.

Would you respond?

Ms. WINCE-SMITH. Well, one thing I think is a very interesting model is how some states—and this is a leadership issue, but some of the leading universities are coming together and forming their own consortiums to identify, within their own respective research

environments, potential innovation and pooling their assets together to both identify and help that.

So we know, you know, universities have special funds for startups. Some of them have actually venture capability. But doing that at a state level more collaboratively and also leveraging with state resources the SBIR grants, Phase I and II, to get a critical mass is one path. Because I think you are completely right. I mean, I hear every day about, oh, somebody has the answer to testing; how do we get to the FDA, you know, for approval?

And so I do think that, yes, there is the federal level. The White House Science Office really should be playing a role in coordinating some of this. But it would be very exciting to see how some of the states themselves and the universities within the states could pool their resources to help on identifying and promoting these startup capabilities coming out of their assets.

And the other thing I think I will mention is, you know, we have talked a lot about demand and the mission focus, but certainly, you know, this is now a national mission to ensure that we have the preparedness, we have the anticipatory R&D investment, so the next time we have a pandemic—and there will be one—we can respond in a resilient, adaptive way and not be scurrying around the way we have had to do this time, really for a lack of organization, I think, not capability.

Ms. JACKSON LEE. No doubt, we shouldn't leave out the small competitors who have possibly a potential for vaccine, for a cure, for good research.

Ms. WINCE-SMITH. We should make sure they are part of the solution. Absolutely.

Ms. JACKSON LEE. Thank you.

Thank you, Mr. Chairman. I yield back.

Chairman YARMUTH. Absolutely.

The gentlewoman's time has expired.

I now yield myself 10 minutes.

Let me, at the outset, thank all of the witnesses for your responses, your testimony, and your candor. It has been an honor to have you as part of the hearing.

You know, when I became Chairman of the Committee, one of the things that I decided we—in a way we could reimagine the Committee, was to talk about different subjects and how they will impact the budget either presently or going forward. So we have had hearings on immigration policy and climate change, and, Ms. Wince-Smith, I know you talked about artificial intelligence. We are going to have a hearing on artificial intelligence and how that might impact the budget.

So the focus has always been these—there are other committees of jurisdiction for these subjects, these issues, but they all have budgetary implications. And that is what we are doing today.

So I think where I would like to start is, in talking about R&D, we talk about its impact on so many things, but what is the potential impact on the budget going forward, whether it is through employment, whether it is through developing new industries and so forth? And what would be the budgetary implications of a reduced or even more of a maintenance level of investment in R&D?

And I will start with our Nobel Prize-winning economist, Dr. Romer.

Dr. ROMER. So I think the investments the United States has made in its university system and its primary and secondary education system from the very beginning, those investments in institutions that raise our skill, that produce human capital, these have been the highest-return investments that we have ever made.

And I think, if we continue to make those, we could have more growth in the future, and we would have more income, more tax revenue, and we would get the benefits of a self-fulfilling, reinforcing cycle. So I think we can't underestimate the importance of investing in people.

Research is one of the ways to invest in people, but it is not the only way. And I think we should really look very carefully at the National Defense Education Act from the 1950's and the kind of indirect support the feds provided for education throughout the nation.

And, in closing, let me just reinforce this point that it is wonderful to be able to draw on talent from all over the world, it is wonderful to encourage the flows of ideas throughout the world, but there is something wrong that we can persuade so few of our citizens, when they are in school, to continue on in graduate school.

And we can fix that. I think by giving the students more control, not making them like serfs working for professors, but empowering them to pursue a career that is exciting to them, we will actually have—we can supplement the international supply of talent with a much deeper, much better educated U.S. body of talent.

Chairman YARMUTH. Ms. Wince-Smith, this is one of the, I guess, the emphases of the Council on Competitiveness. How would you respond to that question? What is our potential downfall if we don't do enough, and what is the potential upside?

Ms. WINCE-SMITH. Well, I very much agree with what Dr. Romer said. So I will give a little different answer, in that we really are living right now in a very low-productivity era. And in order to jump-start our productivity, which really is essential in order to increase the standard of living for all our citizens, we have to really invest in what are going to be the drivers of next-generation productivity. And it really is going to come from not just the research and development investments at universities and labs but how we commercialize at scale all of these capabilities to drive the new industries, products, and services of the future that create value and jobs, you know, that are high-paying for all of our citizens.

So, if we don't invest in the people and we don't invest in these big platform opportunities—and we know they are there; I mean, we don't have to identify them—we will be left behind economically, we will lose global influence, we will not be able to invest and contribute to global challenges in food, energy, water, climate.

And our national security will be very, very weakened. And I think, today, the two come together. You can no longer divide the impact of our economic success from our national security needs as well.

So we have to invest in the people, the platform capabilities, and the infrastructure to deliver it.

Chairman YARMUTH. OK.

Dr. Parikh, I would like you to address that also, but let me add one question to you. In your testimony, when you were talking about the model needing to be adjusted, the Vannevar Bush model needing to be adjusted, you mentioned that the federal government should assume a quarterback's role. If you could explain what that means.

Dr. PARIKH. Yes. Yes. It is not a perfect analogy, but, you know, the federal government is the largest single contributor to that ecosystem. And the federal government can contribute in ways that Vannevar Bush never even imagined, right?

Because there are many models for funding. Dr. Romer has talked about, you know, the need to make sure that our land-grant universities are strong. There are so many different ways. You can fund investigators directly. You can fund ideas. You can fund students. We have to have that approach of creating an ecosystem, many different paths to success. Because those paths are now what is driving everything.

You know, he never imagined that we would be collaborating with—that the pharmaceutical industry would be a global industry, where research that is happening here was going to be complementary with what is happening in Europe. We have to make sure that this new model takes all of that into account and then is really a broad-spectrum support by the federal government.

But then, similarly, the platforms that we spoke about earlier, the federal government can identify those and point us in those directions. That is not to the—not so that there is nothing outside of that, but, certainly, coordinating roles for infectious disease, coordinating roles for artificial intelligence. We know that these are going to be important platforms. We have to make sure that we are investing in them.

Chairman YARMUTH. Dr. Shih, do you want to respond to that question as well?

Dr. SHIH. Well, so let me respond to your original question.

Chairman YARMUTH. That's what I meant, the original question.

Dr. SHIH. Yes. I agree with what Dr. Romer and others have said so far.

OK. One of the other things I want to highlight is that, you know, our investments have been made over many decades, you know, and they have been substantial, right? And they will carry us for some time if we fail to invest enough, but it will decline. We have already seen that in some industries. OK. And it has a long tail. OK. And then rebuilding that is going to be much more expensive.

So we just have to recognize that time lag as well. We are already in the decline in many areas where we can't do those things in the U.S. anymore. All you have to do is look at the source of publications in many fields, and you see it has already shifted to Asia. OK.

So it is a long-term investment. OK. It is beyond one election cycle for sure. All right? But, you know, we need to think in terms of decade-type goals, right?

I mean, when I was growing up, I used to make fun of China's Five-Year Plans, right? Because, you know, Mao Zedong, "Well, we're going to do deep tilling," and he causes a famine in China.

OK? But one thing the Chinese have done well is this kind of long-term planning, OK? And they learn from their mistakes as well, right?

And so I have become less critical of that, as, like, it would be nice to have kind of that longer-term vision, especially when it comes to our capability building and people development.

And I come back to, the capabilities are embodied in people. The people are everything. Right? And so our university system has been tremendous in feeding that pipeline.

And, you know, one other thing I will add. It is like, you don't think anybody in China who has, you know, seen what is in the U.S. and seen the opportunities that are available wouldn't rather live here if they had the chance? OK. And so we continue to be the place that is the most attractive destination in the world. Let's not screw that up.

Chairman YARMUTH. I appreciate that.

And getting to the issue of personnel and talent and so forth, this really is a long-term project, because we need to start figuring out how to get young people attracted to the field. Because you can't just say to somebody who is a senior in high school or a junior in college, "OK, go into research." So it has to start much younger than that.

And one of the things that—I am going to go over my own time, but, again, I have the gavel—is that I think about what we saw in the movie "Hidden Figures" and the Black women who had done extraordinary things but who nobody in the country knew anything about, and I am sure young Black children didn't know anything about that.

Years ago, when I was writing columns, I was doing a Black-history column, and I was doing some research, and I found that—I am an avid golfer—I found out that the golf tee was invented by a Black dentist, G.F. Grant. Who would have ever thought that? And then if you think about George Washington Carver and so many instances—Lewis Latimer, who invented the filament.

And so a lot of it is exposing young people to role models, I would think, as to what their potential is as well. Does anybody want to comment on that briefly?

Dr. PARIKH. Yes, Chairman Yarmuth, if I could.

You know, the AAAS is a gatekeeper organization, right? If you published in Science magazine, you are on your way to an academic career and a research career. You are well on your way. If you get a fellowship from us, you are well on your way.

And one of the things that we noticed is representation matters, right? So, in our fellowship process, there is a very good demographic diversity in the selection committee. And, lo and behold, the awardees are diverse. When you look at our editors of our journals, it is not as diverse, and you see that the publications are not as diverse.

There is something very important about representation and mentorship that we have to make sure that we are not letting this moment hurt.

And I will just speak to this moment for a second. You know, with COVID-19, the disruptions to research, with these immigration policies, and then challenges to our K-12 educational system,

we are in danger of losing a generation of talent in the sciences. And that would be tragic. These are lagging indicators. We are living on the investments that were made in people 10 years ago, 20 years ago.

Chairman YARMUTH. Well——

Dr. ROMER. If I could just echo something that Deborah Winces-Smith said, you know, she pointed to the military academies. The U.S. Government, through the military, has done a very good job on many issues about inclusion and diversity. And they show that if you commit to the principle that everybody can participate and contribute and you live by that standard, you can make that happen.

So I think they should be a model for how the government requires all of our other institutions to do as well as we have done in the military.

Chairman YARMUTH. All right. Thank you for that.

Ms. WINCE-SMITH. Could I add one thing?

Chairman YARMUTH. Go right ahead.

Ms. WINCE-SMITH. One example of a university that has done an incredible job in bringing women and underrepresented minorities into STEM, from the graduate level all the way up through being graduate students, and that is the University of California at Santa Barbara.

They have a completely different model. The moment these young people are freshmen, they are linked with advanced researchers doing Ph.D. work, and they get inspired. And they are mentored all the way through. It is not the traditional thing of, oh, you come into a big chemistry class and by the end of the year three-fourths of you are weeded out.

We have to expand the pool of innovators in the United States. And, again, that doesn't mean that we don't bring others in, and the Council was the first organization that said, staple a green card, you know, for the graduates in our science and engineering enterprise. But we have to bring in our own citizens as part of the enterprise.

Chairman YARMUTH. Well, I will let that be the last word.

Once again, thank you all for your time and wisdom, and we appreciate it very much. I think we have made quite a record here in this hearing.

So thank you, Mr. Flores. I guess you are sitting in as Ranking Member here at the end. I appreciate you being with us.

And, with that, if there is no further business, this hearing is adjourned. Thank you all very much.

[Whereupon, at 3:32 p.m., the Committee was adjourned.]

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CONGRESSWOMAN SHEILA JACKSON LEE OF TEXAS

HEARING STATEMENT:

**“FUELING AMERICAN INNOVATION AND RECOVERY:
THE FEDERAL ROLE IN RESEARCH AND
DEVELOPMENT”**

COMMITTEE ON THE BUDGET

WEBEX

JULY 8, 2020

1:00 P.M.

- Thank you Chairman Yarmuth and Ranking Member Womack for convening this important hearing on the subject of the federal government's role in advancing research and development, especially in light of the current public health crises, economic downturn, and systemic injustices we see today.
- Let me welcome our witnesses:
 - Sudip Parikh, Ph.D.
CEO, American Association for the Advancement of Science
and Executive Publisher, *Science Journals*

- Paul Romer, Ph.D.
Professor at New York University (NYU)
And Co-recipient of the 2018 Nobel Prize in Economics
Sciences
 - The Hon. Deborah Wince-Smith
President and CEO,
Council on Competitiveness
 - Willy Shih, Ph.D.
Professor of Management Practice,
Harvard Business School
- Federal investment in R&D is responsible for laying the groundwork for some of the most critical advancements of our time.
 - The unique capacity of the federal government to invest in long-term, basic research is critical for the flow of new ideas and discoveries that fuel our economy.
 - For example, government-funded R&D created the primary technologies like the microprocessor, battery, hard drive, touchscreen, GPS, and even the internet, all of which lent themselves to creation of the smart phone, which has undoubtedly revolutionized the world we live in.
 - Today, as COVID-19 cases continue to soar across the nation, it is imperative that we increase science and technology funding to learn more about the coronavirus as well as safely and quickly develop vaccines and therapeutics.
 - In the United States alone, we have 3.05 million confirmed cases of the virus and over 133,000 related deaths.
 - Just yesterday, Tuesday, July 7, 2020, Texas reported more than 10,000 new coronavirus cases, setting a new state record for single-day increases.

- This pandemic has irrevocably changed the world as we know it.
- People are angry, people are confused, and people are scared.
- Instead of cutting critical funding or withdrawing from the World Health Organization (WHO), we must recognize science and engineering as important elements in the response to COVID-19 and accelerate our investment in these fields in order to get control over this virus once and for all.
- Despite its immense potential to generate value and scientific discovery, federal R&D funding, as a share of the economy, has fallen from barely 1.9 percent in the mid-1960s to less than 0.7 percent in 2018.
- In comparison, private sector R&D investments have increased, but while doing so, they have shifted towards nearer-term development, thereby leaving gaps in early-stage development efforts.
- Knowledge spillover to competitors and a lack of incentives have resulted in a lack of motivation when it comes to the private sector investing in early-stage technological development.
- If we are to encourage solutions to the coronavirus public health emergency, systemic injustices against minorities, and the recent economic downturn, then we, the federal government, must step in and fill the gaps in long-term funding for early-stage technology development as well as more fundamental research.
- Government R&D funding does not displace private investment.
- Rather, it attracts increased investment.

- In fact, localized clusters of federally supported R&D in labs and universities not only increase regional economic opportunities but also create jobs in both the short and long term.
- By increasing our investment in R&D, we have the opportunity to encourage innovation and secure a sustainable long-run productivity growth for the United States' economy.
- Federal R&D funding has been foundational to our economic prosperity as well as our nation's leadership on the international stage.
- In recent years, we've seen our global competitors emerge as leaders as they ramp up their investments in research and development.
- China, in particular, has been focused on achieving manufacturing dominance in high-tech industries as well as pursuing aggressive practices around intellectual property and acquisition.
- Yet, the United States continues to slip downward on international benchmarks of competitiveness in areas of research and development investment, scientific publications and patents, educational achievement, and workforce diversity and skill levels.
- For instance, since 1995, the United States has slipped from 4th to 10th in a global ranking of R&D expenditures.
- In addition, U.S. patent productivity has fallen by half since 1990.
- Moreover, the current administration's 2021 Budget, would have cut R&D by \$14 billion, or 9 percent of the 2020 enacted level, thereby further stunting innovation.

- In order to maintain and grow our global leadership, we should invest in mission-relevant R&D in areas that align with our national goals and priorities.
- For example, increasing our federal R&D investment in projects related to strengthening our national security, conserving natural resources, improving agricultural productivity, and alleviating poverty both domestically and internationally will allow the United States to achieve new levels of progress that wholly and tangibly benefit all Americans.
- Embracing this path forward means cultivating talent that has been overlooked for far too long by investing in education and training, attracting and retaining immigrants, and eliminating entry barriers for minorities and women.
- Today, children from high-income families are 10 times more likely to become inventors than those from lower-income families.
- Furthermore, Black and Latino Americans represent only 1 to 2 percent of the entrepreneurial and venture capital labor pool.
- If the United States were to target its federal investments to increase diversity, equity, and inclusion in the research and innovation sphere, we would not only see advancements in social justice, boosts in productivity, and accelerated discoveries but we would also be able to increase our GDP per capita by 3 to 4 percent.
- As Members of Congress, it is our responsibility to come together and improve the quality of life for the American people.
- By increasing our federal funding for R&D projects that seek to address and solve some of the world's most pressing and practical problems, we can and will change lives for the better.

- I look forward to hearing from our witnesses.
- Thank you, Mr. Chairman, for convening this important hearing.

Congressman George Holding (R-NC-2)

Statement for the Record

Hearing: *Fueling American Innovation and Recovery:*

The Federal Role in Research and Development

July 8, 2020

I think we can all agree that the last few months battling this pandemic have truly highlighted the invaluable role that private sector research and development, especially in the tech and health care sectors, plays in allowing us to adapt to the world around us.

Americans have had to adjust to an entirely new status quo. Whether joining a staff meeting or seeing a doctor, we've come to rely on innovative technologies to meet our personal and professional needs from home. Telehealth innovations, in particular, have been a key part of maintaining access to care for the most vulnerable portions of our population during this extended quarantine.

I'm proud to say that many of the innovative leaders in global research and development have made their home in my district in North Carolina. Over two hundred and fifty businesses have set up shop in the Research Triangle Park in Raleigh, working on everything from ground-breaking cancer drugs to advanced military equipment.

Unfortunately, many of these companies have been hampered by federal policies that increase the cost of private investment in research and development. For example, the required amortization of R&D expenses starting in 2022 threatens to reduce private investment by over four billion in the first five years and ten billion in the following five. Allowing companies to instead expense R&D investments in the year they were made would allow them to get the full value of their investment and encourage them to direct more of their revenue towards development projects.

Given that private sector funding represents an overwhelming majority of total R&D spending in the United States, I believe we should be working to remove roadblocks and improve incentives for private R&D investments rather than talking about increased federal outlays. For that reason, I urge my colleagues to support common sense policies like changes to the R&D expense amortization requirement to encourage greater private sector investment in the innovations we need.

Questions for the Record
Congresswoman Ilhan Omar
“Fueling American Innovation and Recovery: The Federal Role in Research and Development”
House Budget Committee
July 8th, 2020

Dr. Sudip Parikh & Dr. Paul Romer:

I wanted to give you each an opportunity to discuss the importance of government-university R&D partnerships in general. My district is home to one of the top public research universities in the country, and also happens to be my (graduate school) alma mater, the University of Minnesota. The U of M has become a health care leader in our state and entire nation with their ground-breaking COVID-19 testing and virus research. It was thanks to annual NIH funding that researchers at UMN were recently able to help us understand how the virus that causes COVID binds to its human receptor. Thus, none of this vital research would not be possible without federal support, which constitutes about 60% of the University's awards each year.

Dr. Parikh, why would it be overall beneficial to our economy and society to increase federal R&D funding for U.S. research universities? How does federal R&D increase connections and coalitions among government and universities, and what is your assessment of its impact on scientific discovery and technological innovation to weather this pandemic?

Dr. Romer, what do we know about how federal R&D investments can increase innovation, productivity, and resiliency? Why should we focus on strengthening public sector investments in R&D, rather than only relying on the private sector to try to fill this gap, in order to gain the full economic potential and societal benefit of R&D, pre- and post-COVID?

Rep. Peters' Questions

Dr. Parikh:

- Rady Children's Hospital in La Jolla participated in a pilot project to test that theory. In short, the State of California provided \$2M to enroll pediatric patients with or suspected of having rare diseases in a program to provide whole genome sequencing as a diagnostic tool. What they found was by employing this state-of-the-art diagnostic, Rady was able to return a diagnosis in 43% of cases and result in a change in care for 31% all while preventing 513 days in the hospital, 11 major surgeries, 16 invasive diagnostic tests. In total, the pilot saved \$2.5 million in healthcare costs.
- As illustrated by this example, how do we reduce the barriers to advancing promising medicines and diagnostics?
- How can we reconcile potentially great costs upfront for potential long-term savings, and how can we better account for the long-term benefits?

Dr. Romer:

- What policies and approaches should we avoid to prevent undermining research and development of medicines and diagnostics?

Question from Rep. Ilhan Omar

Dr. Sudip Parikh & Dr. Paul Romer:

I wanted to give you each an opportunity to discuss the importance of government-university R&D partnerships in general. My district is home to one of the top public research universities in the country, and also happens to be my (graduate school) alma mater, the University of Minnesota. The U of M has become a health care leader in our state and entire nation with their ground-breaking COVID-19 testing and virus research. It was thanks to annual NIH funding that researchers at UMN were recently able to help us understand how the virus that causes COVID binds to its human receptor. Thus, none of this vital research would not be possible without federal support, which constitutes about 60% of the University's awards each year.

***Dr. Parikh**, why would it be overall beneficial to our economy and society to increase federal R&D funding for U.S. research universities? How does federal R&D increase connections and coalitions among government and universities, and what is your assessment of its impact on scientific discovery and technological innovation to weather this pandemic?*

Answer: Thank you, Rep. Omar for this question and the wonderful example of the great research contributions from your alma mater, the University of Minnesota. Your example demonstrates how federally funded scientific research conducted at our universities can benefit not only our nation, but in the case of COVID-19, the entire world.

Modern science thrives by building collaborations between disciplines, universities, public and private institutions and even nations. Our own *Science* family of journals publishes numerous impactful research papers on a weekly basis that display these connections and partnerships.

For the United States in particular, studies have demonstrated that federal investments in research and development (R&D) has had a long-term effect not only on American education and invention, but in the creation of modern industry and a highly skilled workforce. According to a study by the National Bureau of Economic Research, federal investments after World War II at U.S. research universities catalyzed a blossoming of “entire local research ecosystems” in a number of states and those regions saw an increase in the number of patents, the creation and growth of high-tech industries, and a higher employment rate lasting three decades.

The formula for this collaborative network is straight forward. The federal government invests in high-risk, high-reward fundamental research at universities across the nation. Because universities tend to perform highly novel and highly influential science, studies have found that university patents are 30% more likely than corporate patents to be cited by future patent filings, suggesting greater influence on future technology trajectories. Furthermore, access to university partnerships and a skilled R&D workforce – both heavily influenced by public research funding in the U.S. – are major factors for locating industrial facilities and research centers. This is particularly true where there's geographic proximity. For instance, the nearby presence of a university (or other public research institution) has been shown to increase innovation in a specific technology sector such as nanotechnology. This is the local research ecosystems that I

refer to that exemplify the increased connections and coalitions generated by federal investments in basic, cutting-edge research.

The impact of this partnership between government, academia and industry to tackle the COVID-19 pandemic could not be more profound. Like many scientists in government laboratories and universities around the world, we at AAAS have pivoted much of our work to respond to the global COVID crisis. The quality and speed of the scientific research papers that we publish in the *Science* family of journals has never been as important as it is now. Our editors are working tirelessly to ensure that high-quality, peer-reviewed research reaches other scientists, policymakers, and the public as fast as possible. While we are working fast, we are not compromising our standards in quality peer-review and data transparency.

Amid the constant information and terrifying headlines, it is important to consider this: the time between the discovery of this novel coronavirus in late 2019, and the discovery of the protein spike that connects to the human receptor was written-up, peer-reviewed and published in approximately two months. Two months. The pace of discovery is astonishing. These findings and others by scientists in China and the United States will form the basis for future treatments and vaccines for COVID-19. This remarkable timeline of discovery – and the treatments they will enable – are made possible by federal dollars.

Question Rep. Scott Peters

Dr. Parikh:

- Rady Children's Hospital in La Jolla participated in a pilot project to test that theory. In short, the State of California provided \$2M to enroll pediatric patients with or suspected of having rare diseases in a program to provide whole genome sequencing as a diagnostic tool. What they found was by employing this state-of-the-art diagnostic, Rady was able to return a diagnosis in 43% of cases and result in a change in care for 31% all while preventing 513 days in the hospital, 11 major surgeries, 16 invasive diagnostic tests. In total, the pilot saved \$2.5 million in healthcare costs.

- As illustrated by this example, how do we reduce the barriers to advancing promising medicines and diagnostics?

- How can we reconcile potentially great costs upfront for potential long-term savings, and how can we better account for the long-term benefits?

Answer: Thank you for this question, which touches on a key reason why robust funding for basic research is so important, and the critical role the federal government plays. As noted in my testimony, private industry tends to have a built-in bias toward incremental advances and familiar markets rather than breakthroughs or new markets. Thus, robust federal funding of fundamental, curiosity-driven research is key to success. Such research is the lifeblood of innovation and the engine that fuels our economy, ensuring that America advances promising medicines and diagnostics, generating long term benefits and savings and securing America's economic future and public health. In addition to the necessities of public research itself, federally funded research provides a critical training ground for tomorrow's scientists, engineers, innovators, and entrepreneurs.

The Rady Children's Hospital offers an inspiring real-life example of this principle in your own district; research funded by federal agencies including NIH, NSF, and DOE paved the way for the whole genome sequencing technology that changed the lives of those young patients. There are many other illustrations of the value of federal funding of biomedical research to be found in the San Diego area; these include a company called [NanoCollect](#), which devised a process to analyze and sort cells for research. In addition, Golden Goose Awardee Hudson Freeze, now at Sanford Burnham Prebys, co-discovered a kind of [bacteria in hot springs](#) that led to the development of PCR, a method for replicating billions of DNA copies from small fragments.

Question from Rep. Ilhan Omar

Dr. Paul Romer, what do we know about how federal R&D investments can increase innovation, productivity, and resiliency? Why should we focus on strengthening public sector investments in R&D, rather than only relying on the private sector to try to fill this gap, in order to gain the full economic potential and societal benefit of R&D, pre- and post-COVID?

Answer: History shows that universities can decisively speed up a nation's rate of economic growth. The uniquely American system of "land grant" universities created by the Morrill Act of 1862 propelled the United States into a position of unquestioned industrial leadership by the middle of the 20th century. As I mentioned in my testimony, the practical technology for pelletizing taconite that was developed by researchers at the University of Minnesota's Mines Experiment Station is a good illustration of the type of contribution that this new type of university made to industrial development. This technology made it possible for the state's Iron Range to supply ore to the nation's rapidly growing steel industry.

No single firm could ever capture all the benefit from the development of this technology. Only universities supported by the Federal and State governments can make investments in this type of a new technology such as this that conveys benefit to the nation as a whole. This was true in the 19th and 20th centuries. It is true now.

Covid illustrates the new type of challenge that we face in this century. The system of public universities that solved crucial challenges in the past are our best bet for solving the challenges we face now. I once wrote that "a crisis is a terrible thing to waste." The best way for the United States to mobilize in the wake of the crisis would be to invest again, as it did in the midst of the crisis of the Civil War, in our public universities.

Question from Rep. Peters

Dr. Paul Romer, what policies and approaches should we avoid to prevent undermining research and development of medicines and diagnostics?

Answer: In recent decades, economists oversold what private firms operating in a market could accomplish. Policymakers from both the Democratic and Republican parties who followed their advice turned away from the approach outlined in the Morrill Act of 1862 — increasing access to higher education and using open science to overcome the practical challenges facing the nation. They turned toward a closed system of proprietary discovery by powerful firms protected by ever stronger property rights. As a result, this nation now has a dysfunctional health care system in which every decision is dictated by the pursuit of profit, not by protection of the public.

To avoid more damage, we need to return to the commitments that worked so well in the past to affordable higher education and to open science as the best way to make progress. We should also look broadly for opportunities in all areas of our health care system — insurance to be sure, but also in the development of new pharmaceuticals and devices, perhaps even in the provision of care. We should even be looking at public options in in other technology-intensive markets where the public now faces a few choices that do not serve their interests.

We need to shift away from policies that have protected the profits of incumbent firms by limiting competition and new entry. We need to return to the insight that economics got right: that the role of policy should be to maximize consumer welfare.

If public options give consumers more choices and better service, our governments should offer them, even if they undermine the profits of incumbent firms.